FIELD AND LABORATORY TESTS OF CONTAMINATED INSULATORS FOR THE DESIGN OF THE STATE ELECTRICITY COMMISSION OF VICTORIA 500 KV SYSTEM

J. Johnson* R. T. Henderson* W. S. Price**

D. E. Hedman*** F. J. Turner ****

In recent years, the control of switching surges by circuit breaker resistors, and the use of shielding angles adequate to reduce lightning impulse flashovers, has made possible appreciable reduction in transmission line insulation levels and cost, particularly on EHV lines. As this process continues, additional design data will be required for the power frequency withstand of line insulators exposed to contamination, if future line designs are to be both successful and economical.

Although extensive investigations have been made during the past two decades on the power frequency performance of contaminated insulators, the basic mechanism is so complex, and there are so many parameters, known and unknown, in the problem that much work remains to be done to permit optimum line design.

Since the future 500 kv transmission system of the State Electricity Commission of Victoria must traverse a very severe contamination area, as indicated by present 220 kv line performance, a very extensive investigation has been made, including both field and laboratory work. This work provided a substantial amount of new design information for the 500 kv system. Details of this study are presented in this paper, for comparison with previous investigations, and possibly to serve as a basis for future research.

FIELD EXPERIENCE

The State Electricity Commission of Victoria supplies virtually all the electric power in the State of Victoria, an area of some 88,000 square miles in the southeastern corner of Australia. Apart from small hydroelectric stations contributing to peak load demands, and a low load factor entitlement from the Snowy Mountains Scheme, the bulk of the power is generated by base load thermal stations situated on the very extensive lignite brown coal fields of the Latrobe Valley, about 90 miles east of the capital city of Melbourne.

Since the first thermal station was installed in 1924, the total capacity of the Latrobe Valley generation has grown to its present level of some 1,400 MW, with a further 1,700 MW of plant under construction or on order, and the probability of extensive additions in the future.

---

* State Electricity Commission of Victoria, Melbourne, Australia.
** Bechtel Corporation, San Francisco, California.
*** General Electric Co., Schenectady, New York.
**** General Electric Co., Pittsfield, Massachusetts.

Initial transmission of power from the Latrobe Valley to Melbourne was by way of four 132 kv steel tower lines which have subsequently been supplemented by six 220 kv lines, and the S.E.C.V. is currently constructing the first of two 500 kv lines which will operate initially at 220 kv and finally at 500 kv in 1970.

If brown coal retains its present economic advantage over other fuels, then it is possible that a total of ten 500 kv lines will be required between the Latrobe Valley and Melbourne by the turn of the century, transmitting a total of some 19,000 MW of base load power, and it was primarily this factor and the associated problems of line easements which influenced the adoption of 500 kv as the next step in voltage.

The original 132 kv transmission lines, and the four 220 kv lines installed between 1956 and 1964 leave the power stations in a westerly direction towards Melbourne, the first 20 miles being located in a shallow valley. The prevailing easterly winds of the dry late summer and early autumn blow the power station plumes along the route of the lines, and the effects of pollution fall-out are readily seen on the insulators up to some 20-25 miles from the stations.

With the assistance of occasional live-line washing in later years, eight 5" x 10" porcelain standard cap and pin insulators on the 132 kv lines and fifteen 5" x 10" standard glass insulators on the 220 kv lines provided effective insulation, even near the power stations. No flashovers due to pollution were experienced, despite the increasing level of pollution, until late 1960 when a trial burning commenced with coal from a newly developed open cut.

In the first three months of 1961 a total of 28 flashovers occurred on the lines in foggy weather, 10 of them being experienced in a single period of one hour between 6 A.M. and 7 A.M. In this latter period, there was a cascade outage of all four 132 kv lines, and it was strongly suspected that the source side transient following upon a fault on one line led to the cascade tripping of the remaining healthy lines. All flashovers occurred on vertical (suspension) strings, and immediate action was taken to secure the lines by the hand application of 0.1 lb. of silicone grease (Dow Corning 5) per insulator on the suspension strings over the first 4-5 miles from the stations. Further greasing has been carried out as flashovers extended beyond the protected zone to a distance of some 10 miles. A total of nearly 90 line outages have occurred during the past five years and all were beyond the zone of protective grease. No pollution flashovers have occurred on greased insulators, which indicates that the protective life of the grease is still effective after three years of service. Strain strings have not been greased and no cases of flashover on these strings have been reported.

FIELD INVESTIGATIONS AND LABORATORY TESTS IN AUSTRALIA

Because of the serious effect of this pollution on the base load transmission, a very thorough field investigation was then started, which led to further tests in laboratories in both Australia and the U.S.

The prime objective of this work was determination of the insulation level to be used for 500 kv lines operating in heavily polluted areas, it being decreed that silicone grease coating is not a solution to the problem until more economic methods of application and maintenance are available.

Better knowledge of the basic mechanism of this type of insulator flashover was a secondary but most important objective.

The field investigations were directed toward:

1. The nature of the pollution and the development of an artificially polluted insulator having characteristics similar to those polluted in the field.

2. Field observation of the flashover phenomenon.

The Pollution

It was very quickly established that the flashovers were associated with the burning of coal from the new Morwell field and that this coal had a much higher proportion of sodium, chlorine, and sulphur than the coal from the earlier Yallourn field. It was also found that the majority of the undeveloped coal fields had similar salty coals, and, therefore, the problem would increase in its magnitude. Plant operating data is given in Table I and the fuel analysis of the two coals is given in Table II.

Many strings removed after flashover were subjected to a "swab" test. From each portion of the disc the pollution was removed by scraping and washing, then filtered, and the conductivity of the measured volume of liquid was determined. From curves of conductivity against per cent solubility the mass equivalent of salt (Na Cl) producing the same conductivity was determined. Typical conductivities are shown in Table III, together with chemical analysis of the pollutants.

Visual examination showed that the deposits of pollution were much heavier on the underside, or protected area, of the insulators and this has been attributed to the combination of electrostatic precipitation and the poorer natural washing of this side of the insulator. It was found, also, that heavier pollution occurred on the downstream side of strain strings, and this appears to be caused by eddying of the flue gases around the insulator under conditions of light wind.

It was observed that at least 4-5 hours of fog conditions prevailed before flashovers commenced, and thereafter the lines continued tripping out for two or three hours - a total of 21 outages occurring in one two-hour period. This process contrasts with coastal salt pollution which is dissolved off the discs much more rapidly in wet or foggy conditions, and if flashovers are going to occur, they take place soon after the right climatic conditions arise.

From this, it was deduced that the pollution had a slow release characteristic for the conducting salts, and that the solubles were bonded to the insulator by a cement-like residue. To obtain some guide to the characteristics, a number of polluted insulators were removed from the line and were placed in a test chamber 10' x 6' x 7'6" high, the thick porous walls of the chamber providing a good measure of temperature and humidity stabilization. The insulators were assembled as vertical strings of eight units and, to simulate clean fog conditions in the field, were left overnight in a relative humidity of nearly 100%. An electronic megohm meter operating from 10 volts d.c. was connected by screened leads to the two ends of the string, and insulation resistance measurements were taken.

Controllable low-pressure steam was injected into the chamber and fans, coolers and moisture-absorbent screens were used to stabilize the temperature and humidity over a five to eight hour test. Insulation resistance measurements were taken at regular intervals, and the average resistance per disc against time from inception of fog was plotted to give Curve A, Fig. 1.

Similar tests were made with clean insulators dipped in salt solution and it was found that there was a radical difference (as shown in Fig. 1, Curve C) between the release characteristics of the power station pollution and natural salt.

To simulate the natural slow release characteristics, the artificial salt pollution was bonded with fresh Portland cement until a curve was obtained which corresponded to that of the naturally polluted insulator. This was achieved by dipping a clean disc in a slurry containing, by weight, 5% to 10% salt in the water used: bonding was provided by adding two parts of cement to five parts of the water in every case. Alternatively, three dips in a 2% salt slurry with drying intervals between dips provided a suitable consistent coating. The insulation resistance-time curve of the artificially polluted insulators is also shown in Fig. 1, Curve B.

It was believed that an equivalent artifically polluted insulator had now been obtained, and this has formed the basis of subsequent tests carried out in Australia and America.

However, it was realised that true comparability with a naturally polluted string at the time of flashover may not have been achieved, because it was usually not possible to remove an insulator from an operating line immediately at time of flashover, and therefore the degree of pollution at that instant was not known - further leaching of solubles occurring in the interval before removal. Secondly, the tests had been carried out in clean fog, whereas it was highly probable that the fog droplets at the power station became conducting while in the plume of the flue gases, and the effect of this on the flashover was not known.

It was found that naturally polluted strings of insulators could not be made to flash over under clean fog conditions at service voltage and that it was necessary to contaminate the fog by the addition of salt. However, it was believed that by varying the salt contamination of the artifically polluted insulators or the salt content of the fog, service flashover conditions could be simulated. For practical reasons the fog was kept clean, and a degree of salt contamination on insulators was established to give approximately the same performance as naturally polluted insulators in polluted fogs in the field. This degree of contamination was then used in laboratory tests.

Field Observations of Surging

Concurrently with the investigation into the pollution, an attempt was made to determine the mechanism of flashover on the suspension strings on the lines. Observers were stationed along the lines at the onset of the autumnal fogs, and the following visual information was obtained:

1. During high rates of moisture release, pear shaped drops have been seen which elongated from the rim and ultimately disappeared with a bright flash between the outer edges of the insulators spaced five inches apart.

2. Shortly after the onset of the fog, a continuous glow developed at the pins and flickering arcs were seen between a pair of outer skirts on the undersides of all insulators with the exception of the line end and upper two insulators of the vertical string.

3. After the fog had persisted for some hours, a change in the phenomenon occurred. The glow at the pins increased in intensity in the lower half of the string, and this was followed by tongues of arcing of increasing luminosity on the undersurfaces of the insulators, and reaching from the pins to the outer edges. A few momentary flashes would occur between separate pairs of insulators and then a bright yellow flash would envelop the lower two-thirds of the string, but without producing complete flashover and resultant line tripout. All glowing and arcing would then cease. This cycle would recommence after several minutes. No arcing was observed on the top sides of the insulators.

4. The arcing described in (3) only occurred under reasonably still atmospheric conditions. It was noted that the arcing immediately became quiescent as soon as the wind velocity exceeded about 5 mph.

   Figure 2 shows a composite record of the meteorological conditions which existed during typical periods when line flashovers occurred, and clearly indicates the effect of wind upon surging and flashover.

5. No more than a faint glow at the pins has been seen on strain strings with the insulators in horizontal arrangement, even during the periods when suspension strings in the same area were undergoing severe arcing. Although no extra insulators were used in the strain strings, and no silicone grease has been applied, no flashovers have ever occurred on these strings.

It was apparent that thermal effects were of considerable importance, and it was reasoned that dry banding was occurring, and that this was appreciably influenced by heat locked up in the vicinity of the cap and pin. This would explain the change to quiescent state at the onset of light winds. It was deduced from the abovementioned observations and the superior performance of the strain strings, where the heat could be naturally convected away from the vicinity of the cap and pin, that flashover was partially dependent on the orientation of the insulators.

Further investigation was obviously required into the mechanism of flashover, and steps were then taken to record the leakage currents on insulators on the lines which were in service, and also to carry out tests on naturally and artifically polluted insulators in a fog chamber with an attempt to propagate flashovers on test strings.

Field Measurements

As a first step towards investigating the mechanism of flashover, it was decided to monitor the leakage currents on the insulator strings on the lines in an attempt to determine the behavior of the insulators at the time of flashover.

At many points of typical pollution conditions along the line route, an extra insulator was inserted at the ground end of a string of insulators. A lightly insulated lead was taken from the pin of this isolating insulator through a protective metal tube clear of power arcs, and thence to the base of the tower. A protective ring spaced about one half an inch above the top side of the second disc from the ground end was provided to terminate power arcs at flashover. Experience has shown that this ring has proved to be effective in taking the power arcs to earth via the lead conduit and safeguards test personnel and equipment. The monitoring lead was taken down the tower to a shorting box near the base and, from these boxes, leads were run back to a test hut in which were located the recording instruments. Graded devices were used to protect against excessive voltage rises should a string develop a power arc.

Initially, chart type pen recorders were used to obtain records of periods at which high leakage currents and surging occurred, and these were started up where prior warning of temperature inversion and probable fogs had been received. It was found that, after some time had elapsed from the start of the fog, the leakage current rose to a steady value of about 2 milliamperes, and then, as moisture began to flow, the insulators went into bursts of surging.

There did not appear to be much difference in the surging records of strain strings and suspension strings, although in the case of the former the high surging commenced earlier without propagating to flashover, and in the case of the suspension strings the surging was delayed, but flashovers eventually occurred.

Attempts were made to obtain more suitable records of the surging currents by the development of transistorized surge counters, in which the triggering amplitude and duration of surge-burst response were independently adjustable. Records showed that quite high random peaks of surging were occurring on operational lines without flashovers taking place, which showed that not all requirements for flashover were present and that some mechanism, possibly thermal, was operating to inhibit string flashover.

Because the transient surge pulses are too fast for analysis by eye on an oscilloscope, oscillographic photography was employed at selected test points, and the basic wave form of the surge current was found to be as shown in Fig. 3.

It soon became apparent that it would not be possible to determine the mechanism of flashover in a reasonable time from records on operational lines, because of the short annual periods of fog and the dangers inherent in reducing the insulation levels to give forced flashovers. Therefore, further investigations were started, in the laboratory with artificially polluted insulators, and in the field by converting one of the 132 kv lines to a test line with strings of differing creepage lengths and arranged in suspension, strain and inverted vee configuration.

Laboratory Tests

Strings of polluted insulators removed from the line and strings of artificially polluted insulators were placed in a fog chamber and voltage was applied with leakage currents being monitored.

Invariably, after a momentary burst of minor surging at the onset of wetting, these strings have withstood about twice service voltage without further surging. As the rate of fog injection was reduced, permitting dry band formation, some minor surging was resumed.

The addition of salt or very dilute H_2SO_4 in the mist readily produced severe surging at field voltage, providing the rate of wetting was sufficiently reduced to permit dry band formation.

Moving film oscillograph records of surge currents and applied voltages during these tests showed that, at each high current surge, the applied voltage had collapsed sufficiently to inhibit flashover. To obtain string flashover during severe surging, it was necessary to raise the voltage considerably, producing a conduction (leakage) flashover, rather than one due to successive voltage fluctuations as in critical surging. For this reason, it was concluded that critical surging tests could only be carried out by a laboratory with ample test capacity or in the field by reducing insulation, thus eliminating the effect of voltage sagging at each surge crest.

The laboratory tests did, however, establish a basic method for carrying out the tests and indicated the importance of the correct degree of wetness in producing dry banding and critical surging.

PITTSFIELD HIGH VOLTAGE LABORATORY TESTS

In order to establish the insulation level needed for the S.E.C.V. 500 kv transmission system between the Latrobe Valley coal fields and the Melbourne area, extensive tests were made on artificially contaminated insulators in the High Voltage Laboratory of the General Electric Company in Pittsfield, Massachusetts.

These tests, which were firmly based on the field and laboratory work carried out in Australia, had the following objectives:

1. Determine the relationship between flashover strength and the severity of contamination, as measured by the per cent salt in the contaminant.
2. Determine the effect of numbers of insulators and total creep distance on flashover strength, to permit extrapolation to 500 kv of the 132 kv and 230 kv operating experience.
3. Determine the relative strength for 60 cycle and switching surge voltages.
4. Determine the relative strengths of vertical and V-strings.

Contamination and Test Procedure

The laboratory tests were designed to simulate as closely as possible the field conditions which produced flashover. For this reason, Locke 5" x 10" insulators with a 12" creepage path were used throughout the investigation. In addition, one test was performed on Ohio Brass 50,000 lb. insulators with a 14.5" creep path.

Since the field observations indicated that the surging phenomenon required several hours to develop into flashover, and since pure salt contamination could not endure for this time period (See Fig. 1, Curve C) the slow-release cement-salt mixture was used to contaminate all insulators. Each insulator was dipped in a slurry made up of 2 parts of cement to 5 parts of water by weight, with 10% salt added, after which the insulator was dried in a warm air atmosphere. In order to lengthen the time that the contaminant would last when testing in a fog atmosphere, each insulator received 3 coats of contaminant in this manner.

The low voltage resistance of the contaminated insulators, as measured in a fog atmosphere, was in the range of 100 to 300 kilo-ohms after about 10 minutes from start of the fog, and remained in this range for several hours, thus duplicating as closely as possible the S.E.C.V. natural contamination. (Fig. 1, Curve A).

The insulators were tested suspended in a fog-filled polyethylene tent 20 feet in diameter and 45 feet high as shown in the drawing, Fig. 4, and photo, Figure 5. A fog was injected in the tent through six nozzles equally spaced around the top circumference, and a high speed fan on the floor kept the fog in suspension and increased the wetting action under the insulator skirts. Voltage was applied to the bottom of the insulator string, and the top was isolated from the grounded supporting cable by three clean insulators. A resistance shunt was connected across the clean insulators to ground, and the leakage current was monitored by measuring the voltage drop across this shunt. This voltage was fed into a log adapter and amplifier, and then recorded by use of a magnetic oscillograph (Visicorder). It was monitored visually on a cathode ray oscilloscope. In addition to the leakage current, the applied voltage was recorded on the magnetic oscillograph by use of a capacitance divider.

Most of the testing was performed with voltage supplied from a 1000 kva 350 kv transformer fed from a 5000 kva 2300 volt generator. The general test method was to apply the voltage at a level that was close to the estimated flashover strength and hold for about fifteen minutes observing the leakage current. This afforded ample time for the insulators to get thoroughly wet. If no flashovers occurred or appeared imminent, the voltage was increased by five percent and held for one to five minutes depending upon the activity observed. This procedure was repeated until a flashover level was established. Alternate methods tried were:

1, to apply voltage at a level where flashover was reasonably certain and decrease in levels until a withstand was obtained; and 2, apply the initial voltage at a definite withstand level until wet, and then increase at the rate of three kv per minute until flashover occurred. All of these methods had some faults, but method (1) seemed to give the best results in that the minimum flashover level was definitely reached before appreciable contaminant was washed from the insulators.

Switching surge tests were run on several strings of insulators after the 60 cycle flashover level had been determined. For these tests five 140 x 3300 microsecond positive polarity waves were applied at a voltage level, and the voltage changed in about five percent levels until the minimum flashover and maximum withstand levels were determined. Complete critical flashover tests could not be run because of the short time available before contaminant washed off the insulators. In all cases, these switching surge tests were made several minutes after completion of the power frequency tests. Although scheduled originally, time did not permit development of a test procedure to apply switching surges during critical surging at power frequency. Therefore, all switching surge data reported represents only the response of line insulation to a surge developed by energizing a dead line, and not to the case where bus transients may produce multiple line flashovers during critical surging.

In all, a total of 75 60 cycle test runs were made, with strings of 5, 15, 30, and 39 insulators, voltages from 33 kv to 240 kv, and various contamination severity levels.

Surging Phenomena

Adjustment of fog, voltage, and contaminant levels produced essentially the same surging phenomena and leakage currents as observed in the field. Figure 6 is a typical record of insulator current, indicating base periods of several milliamperes with no arc activity, interspersed with periods of high current enduring for a second or two and accompanied by arcs on the underside of the insulators. With the proper voltage adjustment, this activity would terminate in flashover.

In addition, high speed current oscillograms duplicated in all major respects the oscillograms of the field operation (Figure 3), providing further proof that the laboratory operation was quite similar to the line operation.

Concise analysis of the surge current records was difficult due to the wide variation in surge timing and magnitude. However, a statistical analysis was made of a number of the Visicorder test records, by dividing the total test period into a number of intervals, and counting the number of cycles of current surges per minute above various threshold levels in each test interval.

Figure 7 shows the results of such ananalysis for a test of 15 vertical insulators with 0.2% salt contamination. 80 kv was held for 15 minutes, followed by a ramp voltage of 2.5 kv per minute. Flashover developed from a 1000 ma surge at 31 minutes, at a voltage of 117.5 kv, or 7.85 kv per insulator. Note that surge magnitude was 20 ma or less during the initial 3-5 minutes of the test, but that frequencies extended to 150 surges per minute. As the test progressed, currents increased to 300-600 ma, and frequencies decreased to about 30 surges per minute.

Figure 8 shows a similar analysis for a 15 unit V-string, with the same contamination and voltage conditions. Flashover occurred shortly after the 29th minute at 117.5 kv. Note that the surge magnitude early in the test was high relative to the vertical string. This phenomena was evident throughout the tests, possibly indicating a somewhat different mechanism for the V-string surging.

Figure 9 shows the surging data for 15 vertical insulators with 0.8% salt. In this test, the voltage was held at 132 kv and flashover occurred at 16 minutes, developing from one of the 250 ma surges.

Effect of Contaminant Severity

As mentioned earlier, tests were run on strings of insulators contaminated with various levels of salt in the contaminant. A large spread of 60 cycle flashover results was obtained, which is usually the case when testing contaminated insulators. These data are shown in Figure 10 where inches of creep distance per kv are plotted against percent salt in the contaminating slurry. This curve might be considered pessimistic in that it goes through the highest points rather than the average level of all tests. It was obvious during the test, however, that these worst conditions were a reality that could be repeated, and therefore should be considered when designing a trouble-free line.

Figure 11 is a semi-log replot of these minimum flashover data, including a calculated concentration of salt for an approximate comparison of measured natural contamination with the laboratory artificial contamination. Also shown on this curve are the minimum flashover levels per insulator at 0.2, 1.0, and 5% salt solution, obtained by dividing the 12" creep per insulator by the specific creep values of the curve.

Figure 12 shows the switching surge withstand test results in terms of specific creep versus contamination severity. Shape of this curve is similar to that of the 60 cycle curve.

The low impedance of the contamination, particularly above 2% salt solution, caused severe regulation of the switching surge tail, such that actual flashovers did not occur in some cases, making the results somewhat difficult to interpret. However, in many cases, the total voltage would regulate suddenly to 30% of normal level, such that the surge crest voltage could be considered a flashover level.

Note that the severe contamination reduced the 60 cycle flashover per insulator from a clean wet catalog value of 50 kv to a range of 6 to 9 kv. However, it appears that moderate contamination, below 2% salt, actually increases the switching surge withstand over the clean wet value, and the very heavy contamination, at 10% salt, causes only a 20% reduction. The insulator switching surge withstand values shown in Figure 12 should be compared with the approximate value of 50 kv clean wet withstand indicated by most of the recent full scale 500 kv tower tests (with the window size permitting all insulator flashovers).

Effect of Number of Insulators On String Flashover Level

The tests indicated that for a given contaminant level there is a linear relation between flashover strength and number of insulators. In one test series where an 0.8% salt solution was used, the flashover strength for five insulators averaged 47 kv and that for fifteen insulators averaged 144 kv, or 9.4 and 9.6 kv per insulator respectively. In another test series using a 2% salt solution, values of 122 kv for fifteen insulators and 294 for 39 insulators were obtained. This represents 8.1 and 7.5 kv per insulator respectively. Considering the spread of results usually obtained in contamination testing, this is considered very good agreement. These and other data are shown in Figure 13.

Effect of Creepage Length

To determine the effect of total creep distance, a string of 15 Ohio Brass 50,000 lb. insulators was tested. Since these insulators are 11-1/2" diameter with a small additional skirt, their creep distance is 14.5" as compared with the 12" creep of the insulators used for the other tests. However, since the shape of the two insulators tested is quite similar, the following test data does not apply to the various fog-type insulator designs now used to obtain extra creep.

The data obtained for these tests are shown in Table IV. It can be seen that for 60 cycle voltage the inches per kv are identical for the two types of insulators, but that the high creep insulators were appreciably stronger for switching surge voltages. Only one switching surge test was made, and therefore in the light of the previous spread of results that have been obtained, the superior switching surge performance of the high creep insulators should not be relied on. The significant fact is that both the 60 cycle and switching surge strengths were increased by the use of high creep insulators to at least the same degree as the creepage length was increased. The switching surge data throughout the investigation was quite erratic and hard to interpret, but the sixty-cycle was under good control for those phases reported herein. From these data it can be concluded that the strength of contaminated insulators is proportional to their creepage lengths for 60 cycle voltages and may increase at a greater rate than the creepage distance for switching surge voltages.

Vee Strings Versus Vertical Strings

A comparison of the strengths of vertical and V-strings was made with strings of 15 insulators for two contamination conditions: 0.8% salt and 2.0% salt. Only one leg of the V-strings was contaminated in order to simplify the leakage current measuring problem.

The data for these tests are given in Table V. For both 0.8% and 2% salt the lowest V-string flashover was ten percent below that of the lowest vertical string flashover. Considering the spread of results that occurred for identical conditions throughout the test program, this is not conclusive evidence that V-strings are weaker than vertical strings. It does make quite certain, however, that for identical laboratory test conditions V-strings are no stronger than vertical strings. This is contrary to actual field experience where it has been observed that V-strings are apt to have higher current surges than vertical strings at the onset of a fog, but no flashovers occur; whereas the vertical strings are slower to develop surging, but once started, they often cascade into a flashover. The initial high current surging noted in field installations on the V-strings was duplicated in the laboratory testing and was attributed to the accumulation of contamination on the lower side due to fog condensation and run off. The fact that in the laboratory tests, flashover for V-strings developed at somewhat lower voltages than for vertical strings, whereas in the field the opposite has been observed, might be attributed to the manner in which contamination accumulates on the insulators in the field. The laboratory dipping method resulted in a fairly even distribution of contaminant.

PITTSFIELD MOTION PICTURE TESTS

During the course of the Pittsfield Laboratory tests, it became clear that a better understanding of the surging and flashover mechanism was required, to explain the orientation effect observed in the field, the shape of the contamination severity curves, the linearity of flashover with creep length, and the arc activity during the many periods of critical surging observed in the field and laboratory.

Therefore a test program was initiated with the primary purpose of establishing a firm description of the flashover phenomena as well as the build up and decay of the surging process when flashover does not occur. It was decided that a high speed movie using approximately 1000 frames per second would be most useful in evaluating the various phenomena and in particular it was desired to obtain a comparison of the vertical and V-string configurations utilized throughout the test program as well as some information on a horizontal string which was not obtained during the more extensive test program.

Test Procedure

The high-speed movie tests used a small fog tent similar to the larger tents used in the previous tests. High speed-movies were taken on tests of

Five Vertical String Insulators
Three Horizontal String Insulators
Three 45 degree (Vee) String Insulators

Two high speed cameras were used in each test. For the vertical string the cameras were oriented such that one would be photographing primarily the under side of the insulators while the other would be photographing primarily the top surface of the insulator. In the horizontal and V-string setup the two cameras were again oriented such that one would be photographing the skirted side of the insulator while the other would be photographing the upper side of the insulator.

Fastex cameras were used for these tests. The camera speeds could be adjusted from approximately 500 frames per second to 3000 frames per second but the speed could not be adjusted precisely prior to any test. Therefore a series of test runs were made to determine the optimum frame speed. The most pertinent results were obtained using the initially proposed 1000 frames per second.

Triggering of the cameras posed some difficult problems. The primary purpose of the program was to evaluate both the build up and the decay of surging as well as the build up subsequent to flashover. A threshold-level triggering circuit was developed which would trigger the cameras at any desired current crest. The threshold-level current monitoring device performed satisfactorily but the delay in camera start following trip signal as well as the substantial time required for the cameras to reach full speed resulted in failure of this approach to the problem. A less sophisticated approach which did have a few shortcomings was developed such that movies of the flashover phenomena could be obtained during the planned test program, as follows:

1. Following triggering of the cameras by a low leakage current surge the source voltage was manually raised to a level which would assure flashover. The delay between the automatic triggering of the cameras by the threshold device and the ability to manually raise the voltage to a level which produced flashover was sufficient to allow the cameras to reach operating speed prior to flashover.

2. The cameras were manually tripped and the source voltage was raised to produce flashover. Again a natural lag in the manual increase voltage produced sufficient delay to allow the cameras to reach operating speed.

Test Results

Performance of the vertical, horizontal, and V-strings will be discussed separately. However, one factor common to all three configurations was a light blue corona glow around the pins of all insulators during the 3 ma base current periods.

The vertical string of five insulators was tested with 2% salt contamination. At this severity 30 to 40 kv, or 6 to 8 kv per insulator, was required to start satisfactory critical surging.

The transition from base current to critical surging occurred within a few cycles. Single arcs extending from the pins toward the outside edge of the undersurface appeared and developed in intensity on all five insulators. The arc paths were maintained through voltage zeros, although of course the light intensity varied directly with the applied voltage. Radial position of the arcs was usually different between insulators and appeared to vary at random. Also, in some cases the arcs extended from the third skirt to the outside edge as the voltage approached maximum and then retracted to the initial position as the voltage increased. The top camera film indicated no arc activity on the top insulator surfaces during critical surging. Therefore, the entire string voltage less underside arc drops, was equally divided among the five top insulator surfaces, causing a high level of string current but without flashover.

Reproduction permitting, underside arcs can be seen on all thirteen of the insulators visible in Figure 5, which was taken during a surging period.

Several 5-15 cycle surging periods which did not develop into flashover were photographed. All arc activity ceased at the end of these periods and the string current decreased from several hundred milliamperes to the base level.

On a number of tests, the manual increase in voltage forced flashovers to develop from surging. Just prior to flashover, all underside arcs were fully extended to the outer edges of the insulators, and in some cases streamers were seen moving around the edge toward the top surface. The flashover was initiated on one of the insulators by an extension of the arc across the top surface to the cap. This extension occurred between two frames, i.e., in less than a millisecond. During the next few cycles, the remaining four insulators, flashed over in the same manner, completing the flashover circuit.

During the 15-20 cycle period following flashover, the ends of the top arcs remained at the outside circumference and at the initial contact point of the cap, while the center portion of the arc moved upward by convection. This movement resulted in consolidation of the five separate insulator arcs into a single arc which then moved away from the string.

A number of tests were made on three horizontal insulators contaminated with 2% salt. 30 to 35 kv, or 10 to 12 kv per insulator was required to produce vigorous surging. Although in general, these surging voltages were approximately 50% higher than those required for the vertical strings, the conclusion that these tests proved the orientation effect observed in the field is not justified, because the quantity of voltage measurements was much too small to be statistically valid. It is interesting to note, however, that the 220 kv horizontal strings in the field have never flashed over while operating at approximately 8.5 kv per insulator.

As on the vertical strings, the surging arcs were initiated at the insulator pins and extended to the outside edge prior to flashover. However, instead of the random variation in radial arc position on the vertical strings, the horizontal arcs tended to rotate to a position above the pin, probably due to thermal convection.

The film also indicated that the surge-to-flashover transition mechanism of the horizontal string was quite different from that of the vertical strings. As the skirt side arcs reached the upper edge of the insulator, they did not immediately flash over to the caps, but instead extended into the air for several inches and then looped back to terminate on the top surface of the insulator at various points. In some cases these long arcs would withdraw to their initial position for a few cycles and then develop into another arc terminating on the top surface. With sufficient voltage the arcs eventually terminated on the caps completing the flashover circuit.

3 unit V-strings were tested with both 2% and 8% salt. As on the horizontal strings, the critical surging voltage was somewhat higher than that required for the vertical strings, but the small record quantity precludes a valid statement on the orientation effect. Generally, the critical surging and transition mechanism was similar to that of the horizontal string for 2% salt.

However, new arc effects appeared on the 8% salt tests. Early in the surging operation separate arcs appeared at various locations on the skirt side, many of them between two skirts. As the voltage forced flashover, these arcs consolidated into two separate arcs extending in different radial directions from the pin to the outside edge. Although these two arcs were absorbing much heavier leakage current from the top surface as they extended to the outside edge, their lengths were no greater than the single arcs seen at lower salt concentrations, and therefore, the insulators were no closer to flashover at any particular stage of the operation. This mechanism constitutes one possible explanation for the shape of the flashover curve shown in Figure 10. In addition, surge arcs were seen originating from the insulator caps across the top surfaces.

ANALYSIS AND DISCUSSION OF RESULTS

For many years, transmission engineers have observed the surging mechanism described in this paper, and have recognized the primary role of this mechanism in producing transmission line flashovers (Ref. 1, 2, 3). Indeed, measurement of the quantity and magnitude of the surges has been an important part of the test procedure at many insulator test stations, such as the stations at Ohio Brass, at Croydon and Brighton in England, at Mons in Belgium, and at Recklinghausen in Germany (Ref. 4, 5, 6).

However, a few of the details of the surge wave shape and mechanism observed during these tests have never been published, to the authors' knowledge, justifying additional discussion of this mechanism and of the other results reported in this paper.

Mechanism of Flashover

The analysis of the growth of an arc from the pin across the ribs on the underside of a polluted insulator to the cap can only be qualitative, because the complex shape of the insulator and the number of variables involved make any mathematical calculation a formidable task. Such factors as the rates of wetting of the pollution due to the fog, the time elements entailed in the drying out of bands under the influence of leakage current, string orientation, wind velocity and the like, and the random nature of step voltages which can occur when a multi-disc string is considered, all inhibit the derivation of formulae to evaluate the probable performance of insulator strings in service. The theories propounded by E. Nasser (Ref. 7) go a long way towards describing the mechanism of an arc on a plain cylinder, but require further development to explain the process entailed when a whole string of insulators is involved. An attempt has been made to set down a qualitative explanation of the phenomena which lead to the flashover of strings of polluted cap and pin disc insulators.

1. From swab tests taken on service insulators, it has been found that the amount of pollution is three times heavier on the underside of the disc then on the upper surface, and if it is assumed that the pollution is evenly distributed on each of the surfaces, then it can be said that the resistance per unit area is at least three times higher on the top side than on the underside of the disc. By dividing the 11" creepage path into 28 bands of 1 cm. width and taking the resistances of the bands to be proportional to the reciprocals of their mean diameters, we can plot a curve of the resistance of each successive band. The "Fully Wet" Curve Figure 14 is such a curve for a polluted disc removed from service and is formed by plotting the resistance of the successive bands when the insulator is fully wetted and is carrying no leakage current. It will be noted that the resistance is far from uniform across the disc, and in fact is comparatively highly concentrated in the vicinity of both the cap and the pin.

2. As damping due to the fog commences, the resistance reduces in line with the I.R. - time curve of Figure 1 and leakage current starts to rise, as has been shown on the chart records. This gives rise to concentrated local heating in the vicinity of the cap and pin, which tends to dry out the pollution in those zones, in turn increasing the resistance and limiting the increase in leakage current.

3. Away from the cap and pin, the resistance continues to fall, and this further distorts the distribution of resistance across the disc as is shown by the progressive curves in Figure 14.

4. The voltage distribution across the disc is considerably distorted in line with the resistance distribution (see Figure 15), and because of the higher electrical stress in the vicinity of the small diameter pin, a glow discharge commences and ultimately an arc is struck across the dry band on the underside of the disc. The electrical stress is lower in the vicinity of the cap, and this phenomenon does not occur there, although the voltage gradient is high and dry banding is proceeding.

5. When the arc is struck, there is a sharp rise in leakage current, as evidenced by surging on the chart record, but in the early stages the arc length is limited by the ballast resistances of the main body of the disc and the dry band at the cap. Initially, the arc strikes to the first rib on the underside of the disc.

6. The arc root is centred on the first rib, and if it is not to extinguish, then it must maintain its current in one of two ways, as the area around the arc root dries out: -

   (a) Move to one edge of the dry band and rotate around the rib with the dry band following it.

   (b) Remain approximately centred in the dry band feeding on the edges as the band increases in area by a number of filamentary arcs which flow from the arc products and ionised air which are being released by the arc and which are trapped in this location.

   Probably there are elements of both of these in the actual behavior, but by and large the arc tends to remain rooted in one position.

7. The sharp rise in leakage current generates appreciable heat in the vicinity of the cap and this results in an increase in the ballast resistance at this point. This has the effect of reducing the arc current and reducing the arc voltage to the point where the arc goes out. This explains the short duration of those critical surging periods not terminating in flashover.

8. After arc extinction, the process restarts with wetting down of the pollution and distortion of voltage across the insulator until a fresh arc is started again.

9. If the fog persists, the total resistance of the insulator reduces, and the arc can strike with more current and over a longer length. The ballast resistance of the main body of the disc becomes less effective, and the control is now being exerted mainly by the dry band in the vicinity of the cap. The surging becomes more violent and the stage can be reached where there is insufficient time for increase in ballast resistance at the cap to prevent extension of the arc to the rim of the disc and ultimately to flashover.

10. Two further factors may now have an effect upon the behavior of the arc. Firstly, there may be step changes of voltage and current applied in one insulator by sudden arcs being struck on other insulators, if the whole process is not synchronized on all insulators simultaneously, and this may result in lengthening of the arc or cascade development where arcs are about to be struck across dry bands. Secondly, the performance of

long arcs may be modified by low resistance shunt paths, which exist in those portions of the insulator not bridged by the arc, which will tend to inhibit the growth of arc length - this factor being of more significance where the string is tilted and thus moisture tends to be unevenly distributed over theinsulator area.

11. When the arc reaches the rim of the insulator, its further propagation is influenced by the orientation of the string, since in suspension strings it is possible for the arc to rise with the ionised gases and to enter the arc on the underside of the insulator immediately above it. This will give rise to very rapid flashover since all control of the arc has been removed by the shorting out of the ballast resistances.

12. The superior performance of V-strings and strain strings is believed to be due to three primary factors -

    (a) The better cooling by convection which improves the differential rate of dry banding at the cap and at the pin, thereby permitting the ballast resistance at the cap to exercise more control.

    (b) A higher conductivity shunt path across the arc due to moisture flowing down the tilted insulators.

    (c) The better dispersion of ionised gases, due to convection air currents moving these gases away from the insulator string. Note that this same effect may also account for the cessation of surging on vertical strings when the wind velocity increases to above 5 mph.

Line Design

The saturation shape of the flashover-contamination curves of Figures 10 & 11 gives promise that lines with cap and pin insulators can be designed to operate successfully in highly contaminated areas, since it appears unnecessary to increase insulation linearly with the amount of contamination. For instance, a line with 10% margin above the 1.7 inches/kv specific creep at 2% salt contamination could withstand without flashover a very substantial increase in contamination such as might occur during salt fogs or other sources of temporary contamination.

On the other hand, lines operating below the knee of the curves, say at 1.3 inches/kv, as on the S.E.C.V. 220 kv lines, would flashover with short-term increases in pollution level, in spite of frequent live-line washings.

Furthermore, it appears that high creep insulators with standard cross-section, such as the 17" and 18" designs now available, can be used to obtain the required level, at some saving in string length and tower steel. However, the use of this design philosophy with other insulator shapes, such as the various fog-type designs, is not warranted pending further field and laboratory experience, since the high speed movies and the authors' theoretical studies clearly indicate the importance of insulator shape to the critical surging mechanism.

Therefore, a reasonable 500 kv line design to operate in heavily contaminated areas might have 1.8 inches/kv specific creep, or 540 inches total creep at 300 kv L-G, this creep distance provided by 32 insulators with 17" creep. This design assumes vertical strings.

In spite of the negative results obtained on the few V-string tests of the Pittsfield investigation, the weight of the evidence at this time indicates that this insulation level would perform better in vee configuration, as follows:

1. Superior performance of horizontal strings in the field and the cessation of critical surging on vertical strings with wind velocity above 5 mph.

2. The difference in surge-to-flashover transition mechanism, as observed on the high speed films.

3. Theoretical studies presented in the previous section.

High Speed Movies

The wealth of information on the critical surging mechanism provided by the high speed movies was so great that detailed analysis is still in progress and cannot be presented in this paper. This method of test together with good recording of string current and voltages, is commended to other researchers in this field.

Typical of the data provided by these tests is the following observation. As moderate surging develops toward severe surging, the arc reignition point, (See Fig. 3B) decreases from about 70° after zero to about 30°. As the arc reaches the point of no return, the ignition advance takes place in steps, and the ignition point gradually decreases to about 20° to 5°. Once the power follow arc commences, the ignition point is at current zero and the wave form is approximately sinusoidal.

The surging and flashover mechanism observed during these tests did not conform to current theory (Ref. 1) which postulates that the instability caused by dry banding produces complete flashover of one or more insulators in the string, with arc inactivity on the other insulators.

For instance, the transition from base to surge current and resultant undersurface arc activity occurred within a few cycles on all insulators in the string. This might be expected from the results of a recently completed digital computer analysis of voltage grading on contaminated insulators (Ref. 8). In the terminology of the reference paper, q of the insulators with this amount of contamination is approximately 400, with an X_c per insulator of 80 megohms, and an R per insulator of 0.2 megohm (See Fig. 1). With this value of q, all computer solutions presented in Ref. 8 indicate essentially linear voltage and power grading, even considering all possible capacitance fields.

During the critical surging operation, there were a few variations in arc length and position between insulators, as noted above. However, as the operation approached the surge-to-flashover transition point, all insulators in the string were arcing in the same manner and parallel in time, at least within the millisecond time resolution permitted by the test procedure. Therefore, the linearity of string flashover with number of insulators shown in Fig. 13 could be expected, because all insulators share equally in the transition to flashover.

CONCLUSIONS

1. The critical surging mechanism observed in the field and laboratory appears to be the prime factor in producing power frequency flashovers, with the S.E.C.V. type of contamination, and possibly with most or all other types of contamination.

2. The severe contamination studied reduces insulator power frequency flashover level from the 50 kv clean wet value to a range of 6 to 9 kv per insulator.

3. Shape of the flashover-contamination severity curves indicates that an insulation level, necessarily high, can be chosen which will operate satisfactorily in the most severe contamination areas.

4. It appears that the moderate contaminations tested increase the switching surge withstand above the clean wet value, while the most severe contamination reduces these values to approximately 20% below the clean level.

5. For the standard cap and pin insulator shapes tested, string flashover is linear with number of insulators from 5 to 39, at the same contamination severity.

6. Within the test limits, power frequency flashover is approximately proportional to total creep distance.

7. Although much additional research is required for proof, the weight of the present field and laboratory evidence indicates that horizontal and V-strings have a higher flashover level than vertical strings, because of fundamental differences in the critical surging and flashover mechanisms.

REFERENCES

1. The Characteristics and Performance in Service of High Voltage Porcelain Insulators, J. S. Forrest. Proceedings of IEE, 1942, Vol. 89, page 60.

2. Performance of Dust Contaminated Insulators in Fog. Bradley Cozzens, T. M. Blakeslee. AIEE Transactions, Vol. 67, 1948, pp. 1686-91.

3. Insulators to Withstand Air-Borne Deposits. J. J. Taylor, AIEE Transactions, Vol. 67, 1948, pp. 1436-1441.

4. Research on the Performance of High-Voltage Insulators in Polluted Atmospheres, J. S. Forrest, P. J. Lambeth, D. F. Oakeshott. Proceedings IEE, 1960, Vol. 107, pp. 172-180.

5. Behavior of Line Insulators and Line Equipment Under Conditions of Natural and Artificial Pollution. Belgian Experiments. C. Gregoire, 1964 CIGRE Paper No. 211.

6. New Field Experience with Outdoor Insulators in Pollution Areas and Methods of Assessing the Performance of Insulation under Conditions of Pollution, H. Baatz, S. Boll, O. Brennecke, G. Niehage, G. Reverey, T. Vogelsang. 1964 CIGRE Paper No. 212.

7. Zum Problem Des Fremdschichtuberschlages An Isolatoren. E. Nasser. Electrotechnishe Zeitschrift. ETZ-A, May 1962, V. 83, pp. 356-365.

8. Contamination of EHV Insulation -I. An Analytical Study, E. W. Boehne, G. S. Wiener. IEEE Paper 31-PP 66-481. Presented at New Orleans Summer Meeting, July, 1966.

TABLE I

LATROBE VALLEY POWER STATIONS

	Yallourn						Morwell	Hazelwood
	A	B	C	D	E	Briq. Factory		
Years of Commissioning	1924-1928	1932-1938	1954-1957	1958-1959	1961-1962	1924 1931	1958-1961	1964 Onwards
Capacity MW	75	100	106	100	240	21, plus Process Steam	170, plus Process Steam	600 (late 1966)
Source of Coal	Yallourn O. C.	Yallourn O. C.	Morwell O. C.	Yallourn O. C.	Yallourn O. C.	Yallourn O. C.	Morwell O. C.	Morwell Open Cut
Approximate Normal Daily Coal Consumption, tons	7,500		5,000	6,000	10,000	3,000	3,500	20,000
Dust Collectors Installed on Boilers	None	None	Multiclone	Multiclone	Multivortex	Some Multiclones	Centicell	Electrostatic Precipitator

TABLE II

COAL ANALYSES

	Yallourn Open Cut *		Morwell Open Cut **	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit
Moisture Content (% in coal as received)	63.5	70.5	60.6	62.5
Coal Constituents (% in dry coal)				
Ash Content	0.6	2.6	3.1	4.8
Carbon	64.5	67.5	64.8	68.8
Hydrogen	4.50	4.90	4.60	4.90
Sulphur	0.11	0.43	0.51	1.19
Chlorine	0.01	0.11	0.08	0.25
Ash Constituents (% in dry coal)				
$Si0_2$	0.02	1.00	0.07	0.90
Al_20_3	0.02	0.94	0.05	0.20
Fo_20_3	0.18	0.72	0.27	0.68
$Ca0$	0.02	0.20	0.67	0.96
$Mg0$	0.12	0.36	0.63	0.89
Na_20	0.04	0.10	0.25	0.50

Upper and lower limits include 95% of values of constituents.

* From Specification for Yallourn "W" Power Station.

** Weekly Coal Deliveries to Hazelwood Power Station.

Ash constituents not listed comprise principally sulphate (SO_3) which contributes 20-40% of the ash content, and which is combined with the sodium and part of the calcium contents, and chloride (Cl), potassium oxide (K_20), titanium oxide ($Ti0_2$) which are present in small amounts.

TABLE III - TYPICAL POLLUTION CONCENTRATIONS ON LINE DISCS

	Disc P9	Disc 56-10
Distance of line disc from power station	0.5 mile	10 miles
String arrangement	8 discs vertical	15 discs vertical
Service voltage	132 kV	220 kV
Years disc in service	2-1/2	10
Size of disc	10"x5"x15000 lb.	10"x5"x11000 lb.
Disc material	glass	porcelain
Surface creepage distance - inches	11.3	11.6
Disc maintenance	No washing	Washed each 2nd Yr.
Date of flashovers	21, 12, 65	2, 3, 65 (Washing due)
Weather conditions at flashover	Light smog	Severe smog

		Top	Bottom	Top	Bottom
Conductivity					
Equivalent NaCl on surface	mg	66.0	822.5	14.8	156.0
Equivalent NaCl concentration	mg/cm^2	0.112	1.13	0.024	0.19
Area of polluted surface	cm^2	590	730	610	820
Insolubles					
Water - insoluble pollution	mg/cm^2	0.49	6.9	0.038	2.0

Composition of main constituents of water-soluble pollution
(for disc 56-9 adjacent to disc 56-10 above)

			Representative Values	
			Top	Bottom
Sodium	as Na	%	5.5	1.3
Calcium	as Ca	%	11.0	17.6
Magnesium	as Mg	%	7.2	3.4
Chloride	as Cl	%	11.0	3.1
Sulphate	as SO_4	%	45.2	50.5

TABLE IV

Sixty-Cycle and Switching Surge Strength of Standard and High Creep Insulators with 2% Salt Contamination.

		60 Cycle		Switching Surge	
No. Ins.	Creep inches	F.O. kv-rms	inches/kv	F.O. kv-crest	inches/kv
15	12	118	1.53	710	.253
15	14.5	143	1.52	1180	.184

TABLE V

Comparison of Sixty-Cycle Strengths of Vertical and V-strings.

Lowest Flashover KV - RMS

0.8% Salt		2% Salt	
Vertical	V-string	Vertical	V-string
132	119	122	118
145	119	118	106
Average 139	119	120	112

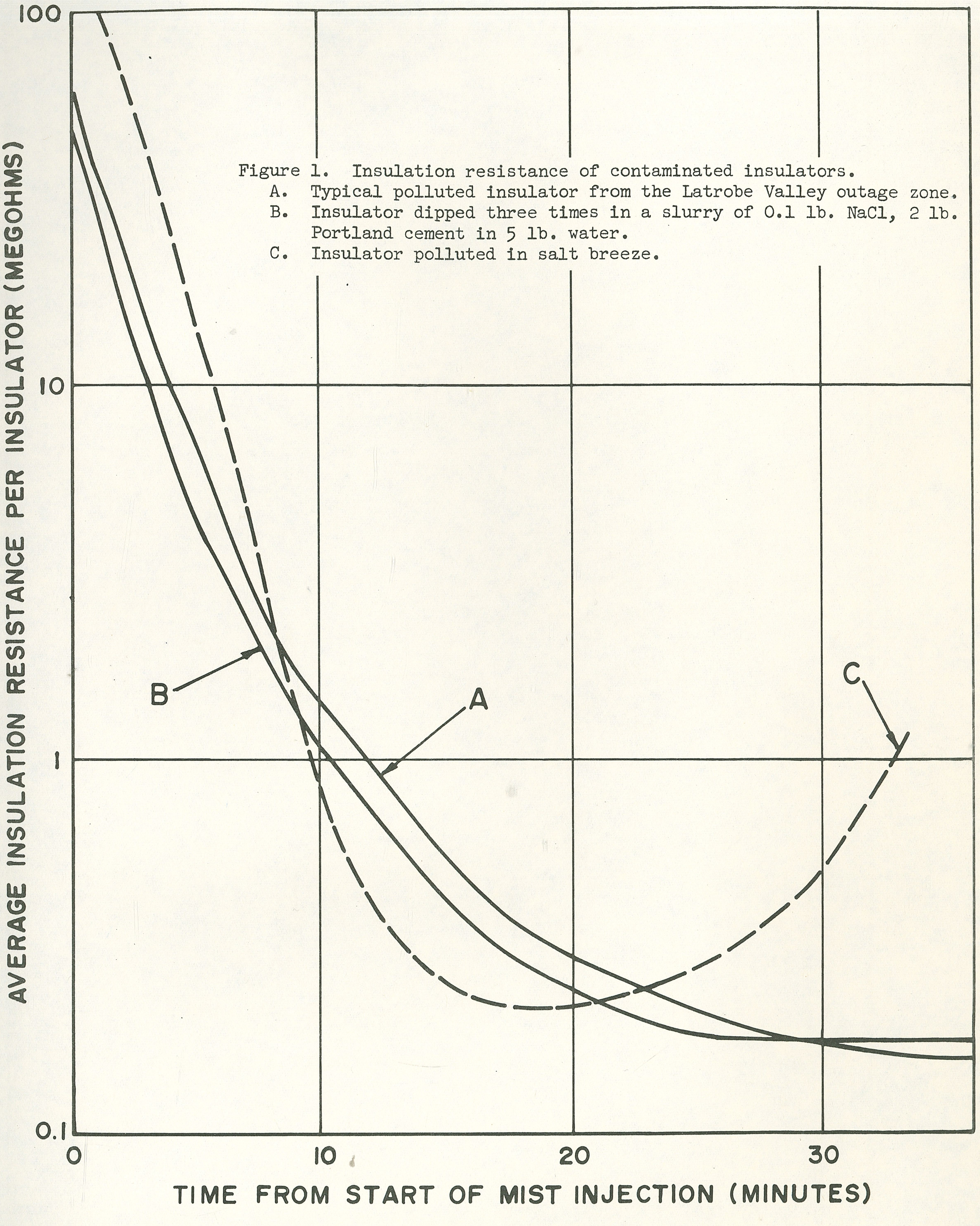

Figure 1. Insulation resistance of contaminated insulators.
A. Typical polluted insulator from the Latrobe Valley outage zone.
B. Insulator dipped three times in a slurry of 0.1 lb. NaCl, 2 lb. Portland cement in 5 lb. water.
C. Insulator polluted in salt breeze.

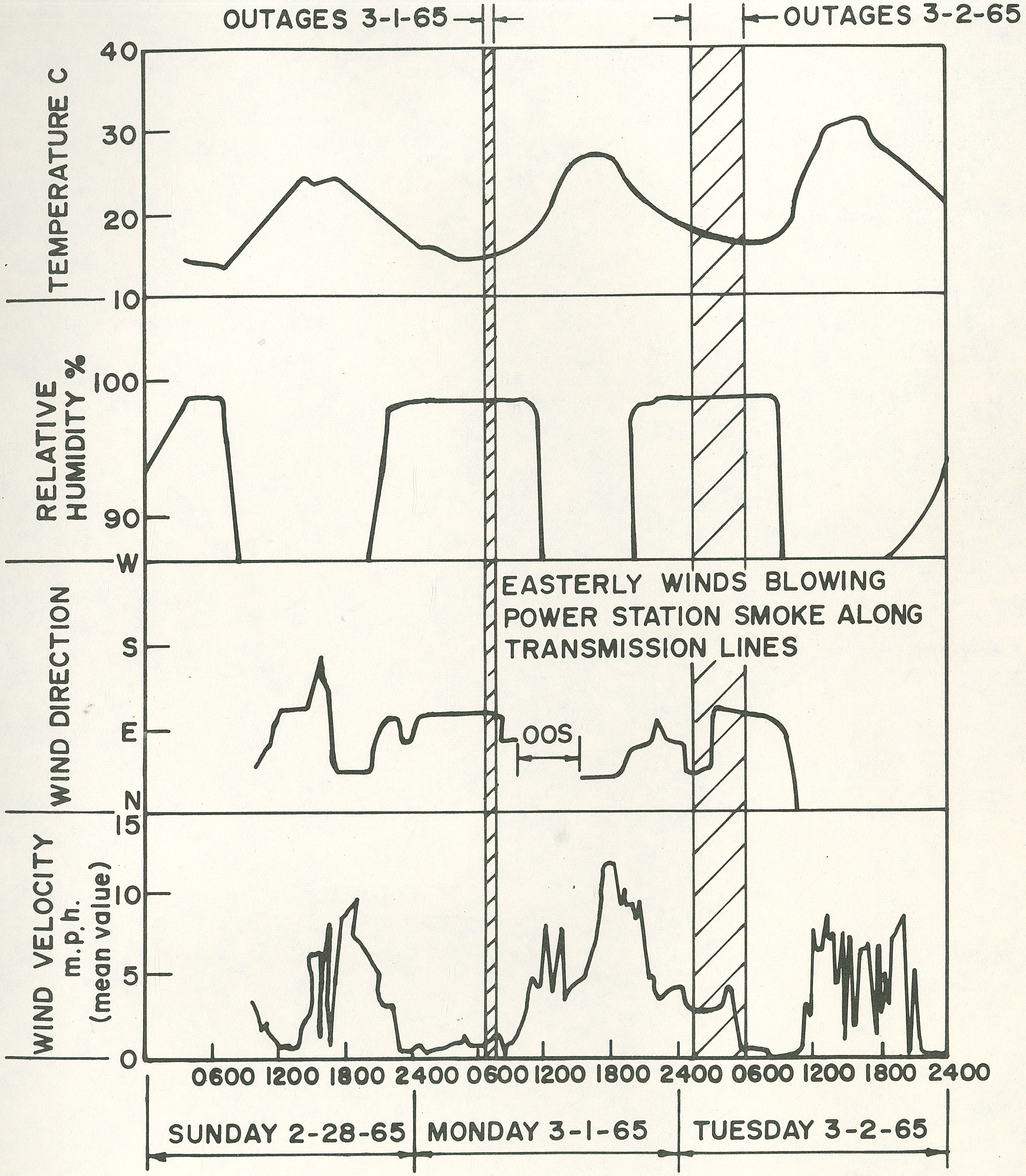

Figure 2. Typical meteorological conditions during outage period.

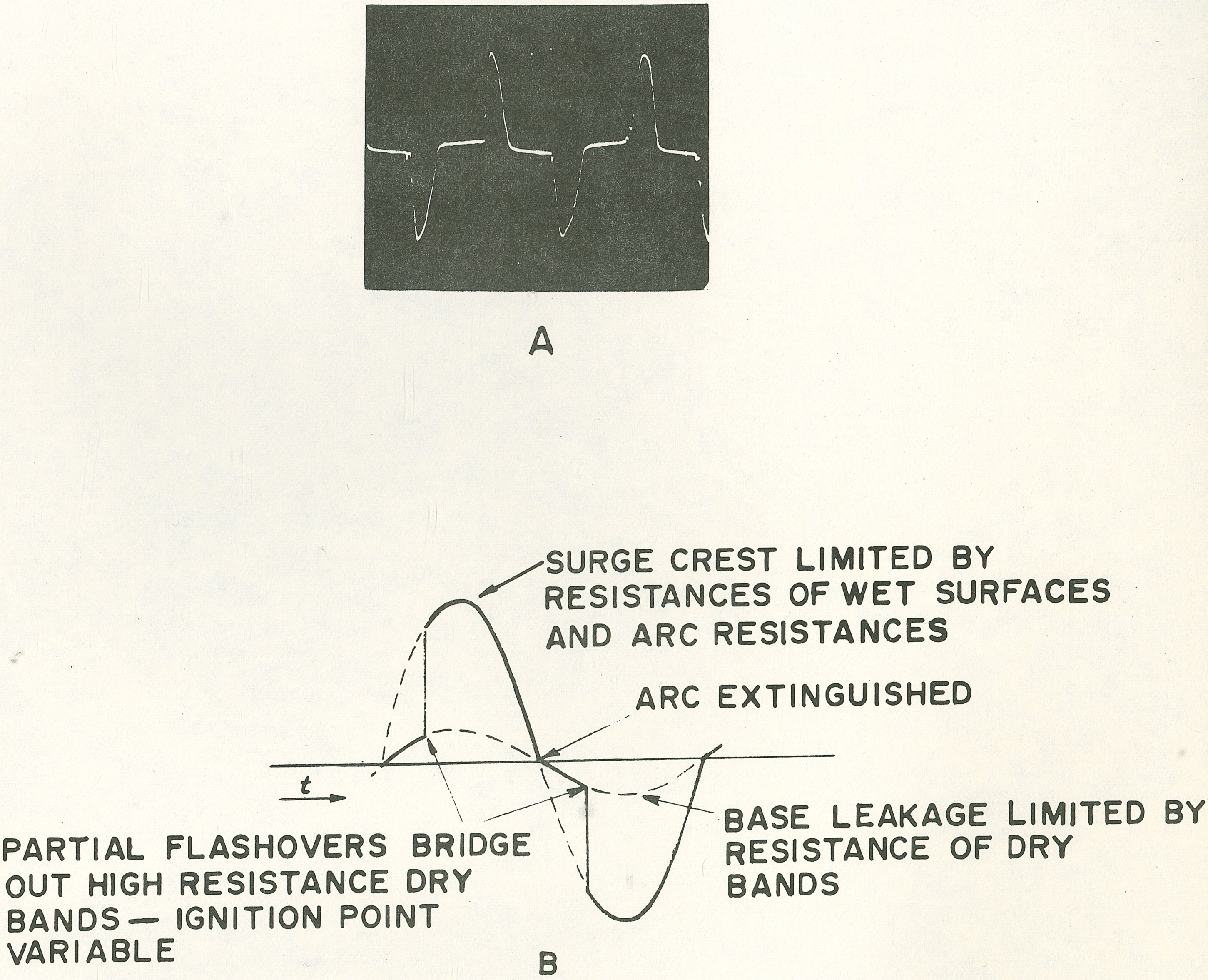
A
SURGE CREST LIMITED BY RESISTANCES OF WET SURFACES AND ARC RESISTANCES
ARC EXTINGUISHED
t
BASE LEAKAGE LIMITED BY RESISTANCE OF DRY BANDS
PARTIAL FLASHOVERS BRIDGE OUT HIGH RESISTANCE DRY BANDS— IGNITION POINT VARIABLE
B

Figure 3. Basic wave forms of surge currents.
A. Field oscillogram of minor surging - 15 ma peak.
B. Interpretation of wave form.

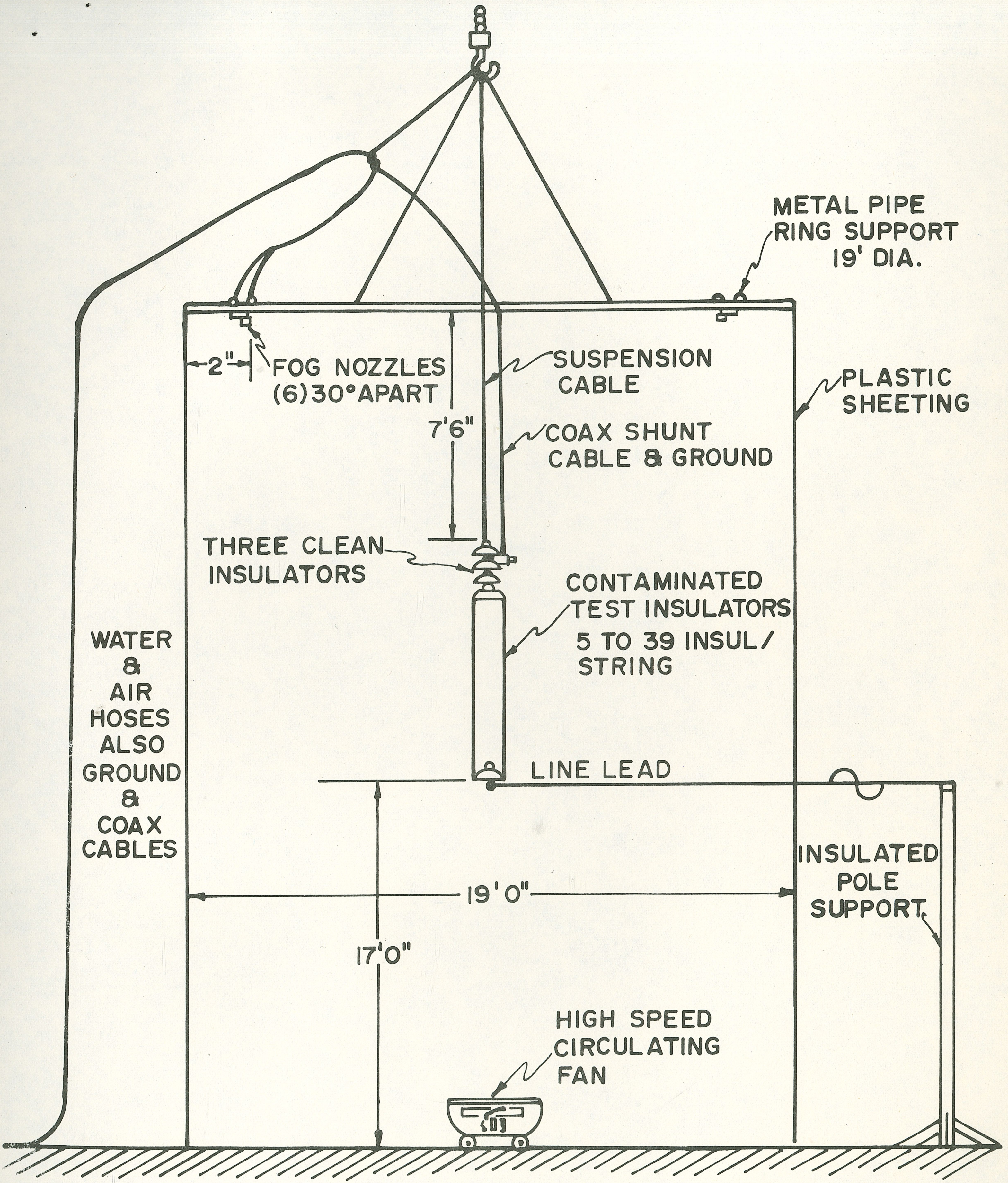
METAL PIPE RING SUPPORT 19' DIA.
2"
FOG NOZZLES (6) 30° APART
SUSPENSION CABLE
PLASTIC SHEETING
7'6"
COAX SHUNT CABLE & GROUND
THREE CLEAN INSULATORS
CONTAMINATED TEST INSULATORS 5 TO 39 INSUL/ STRING
WATER & AIR HOSES ALSO GROUND & COAX CABLES
LINE LEAD
INSULATED POLE SUPPORT
19'0"
17'0"
HIGH SPEED CIRCULATING FAN

Figure 4. Fog chamber arrangement.

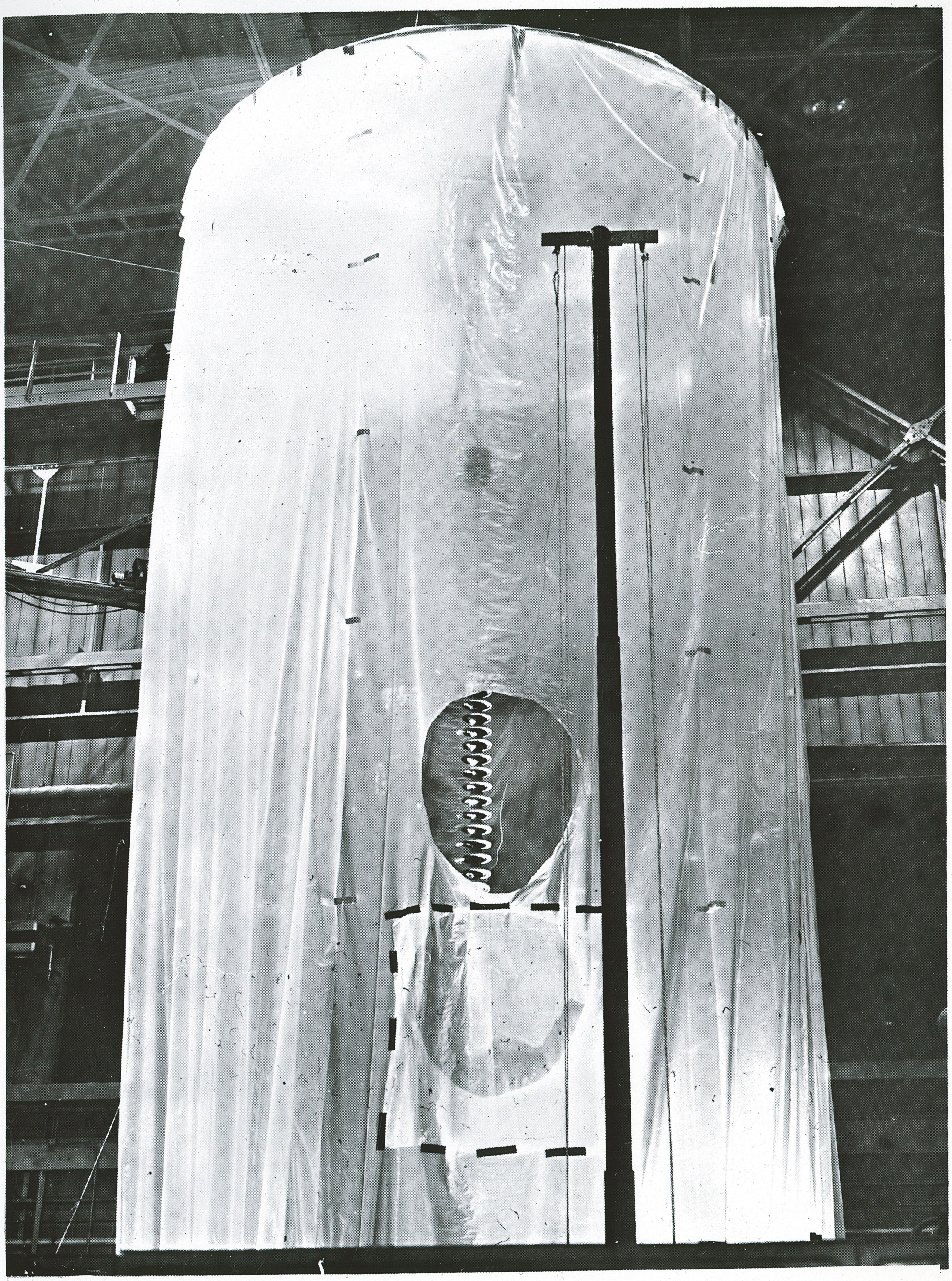

Figure 5. Fog chamber and insulators under test.

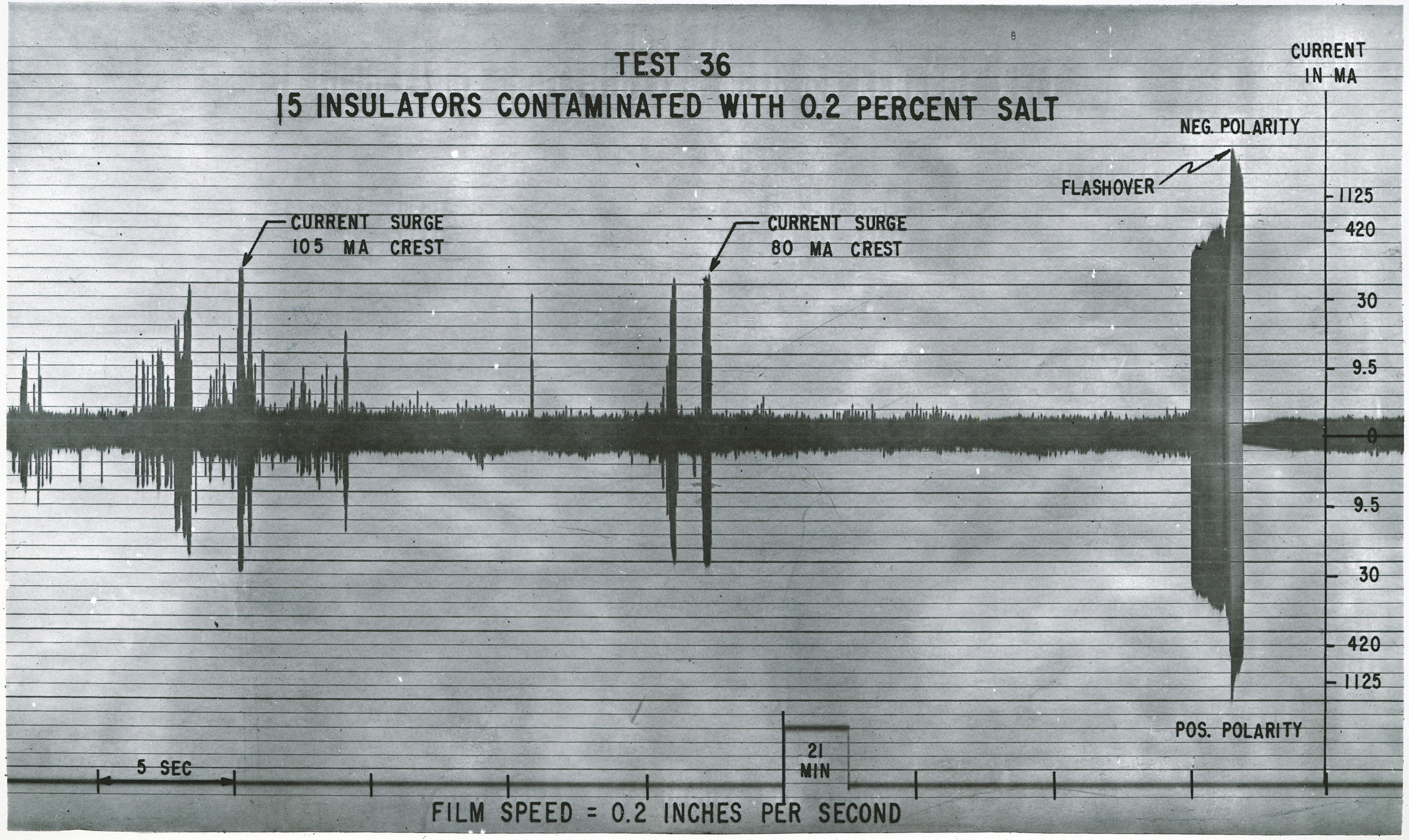

Figure 6. Surge current record - Test 36.

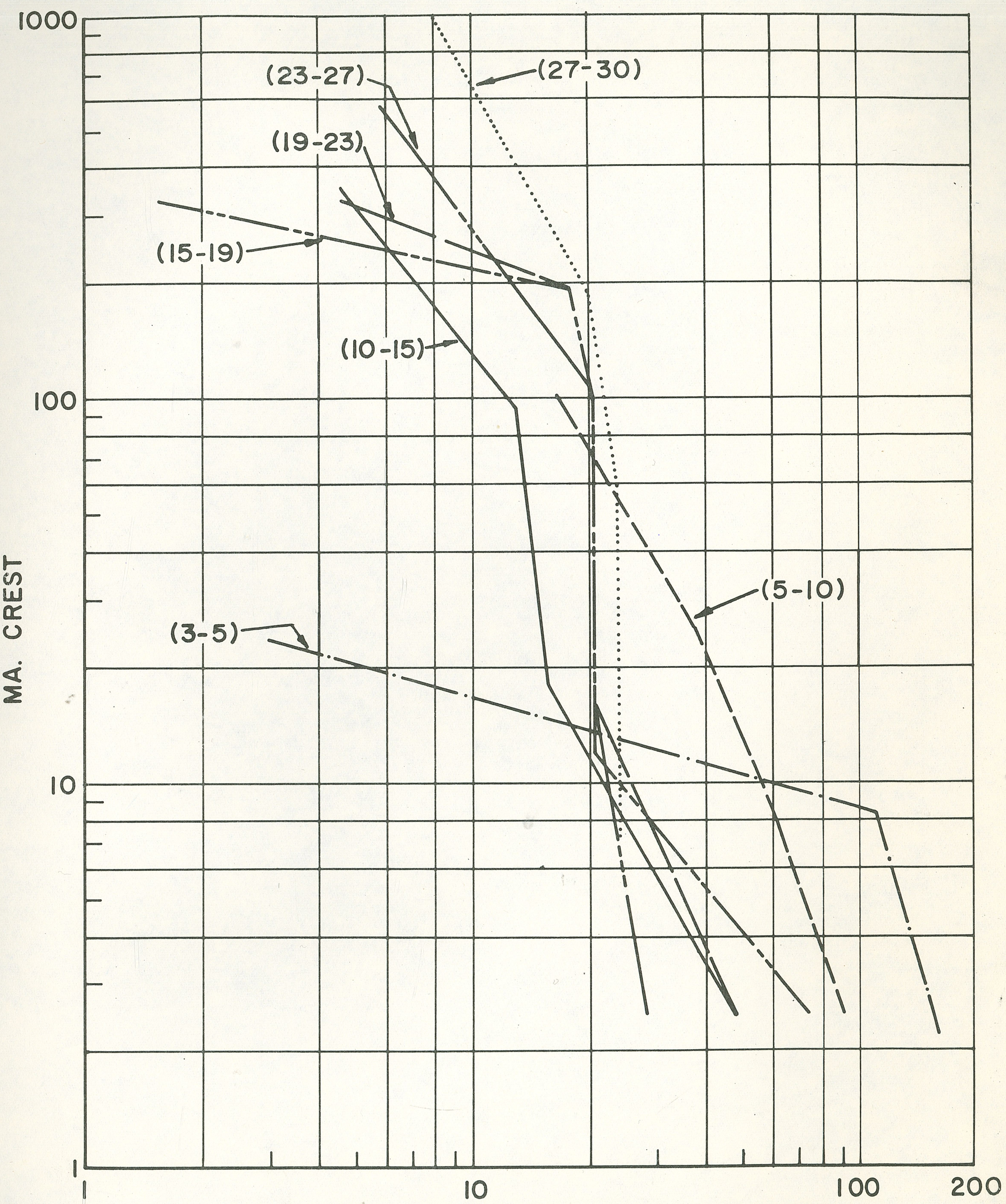

Figure 7. Surge analysis - 15 vertical insulators with 0.2% salt contamination. Curve designations are time period in minutes, measured from start of fog.

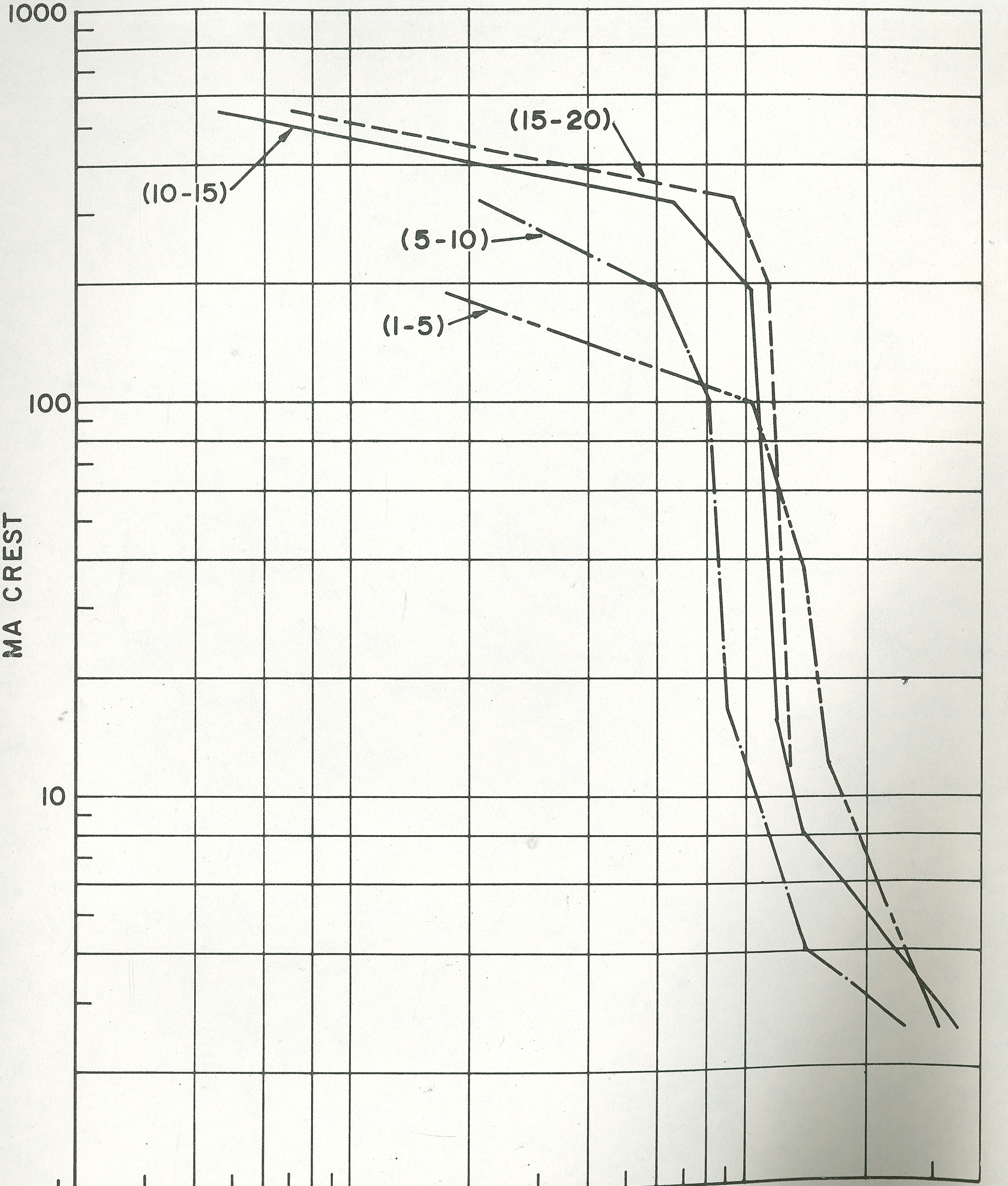

Figure 8. Surge analysis - 15 vee insulators with 0.2% salt contamination. Curve designations are time period in minutes, measured from start of fog.

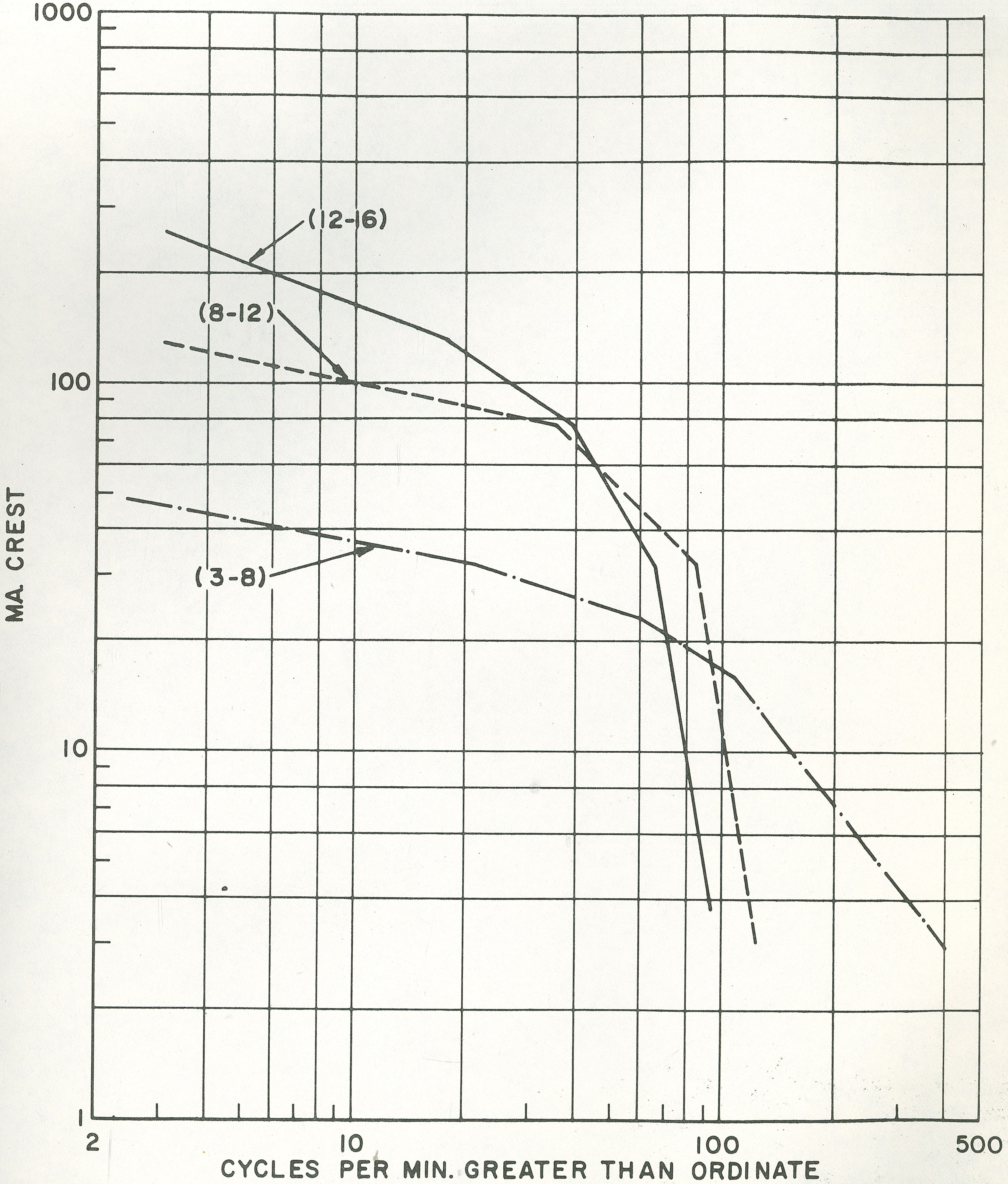

Figure 9. Surge analysis - 15 vertical insulators with 0.8% salt contamination. Curve designations are time period in minutes, measured from start of fog.

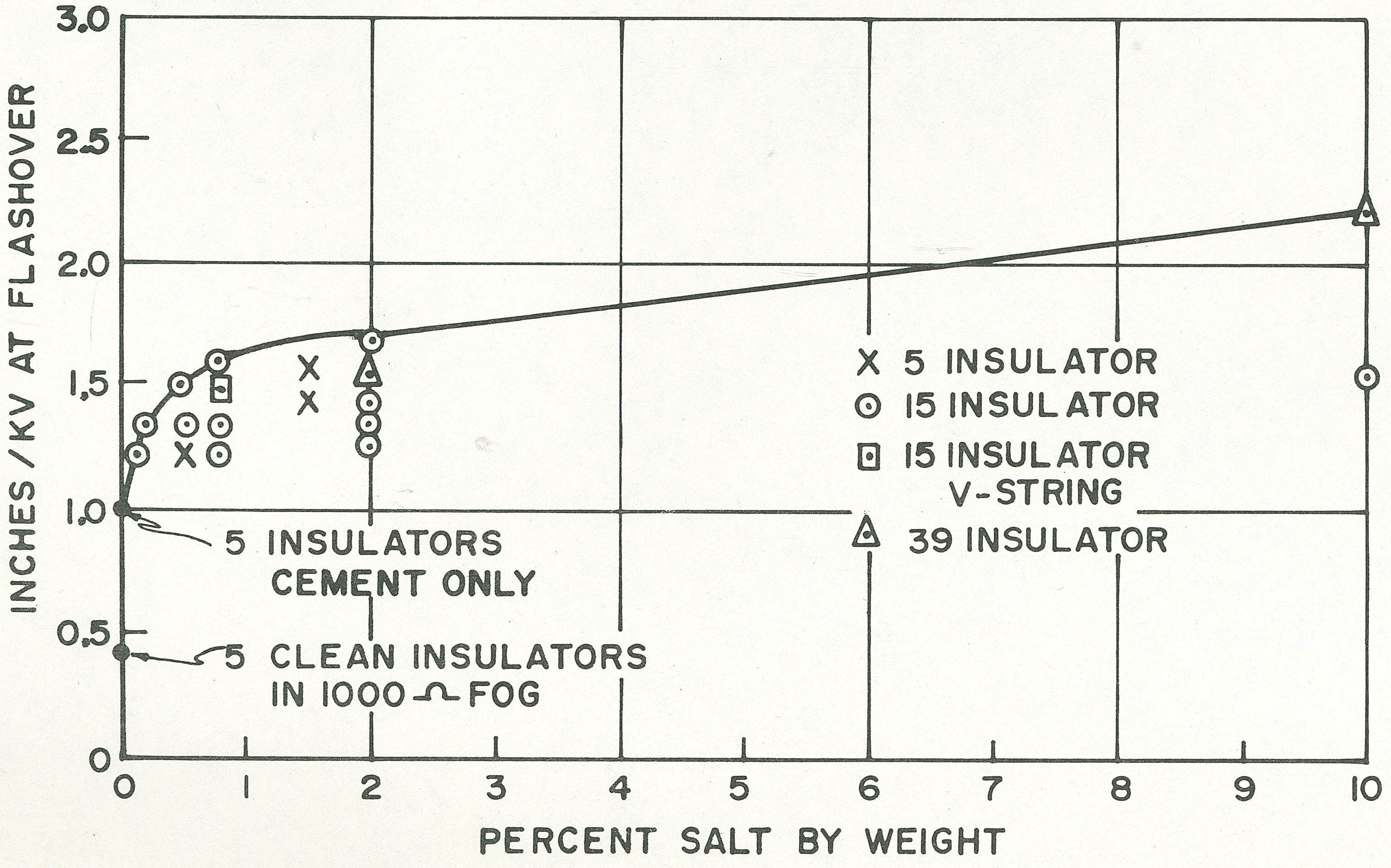

Figure 10. Inches of creepage per kv applied at 60 cycle flashover versus salt content of contaminant. Linear plot.

ALL VERT.

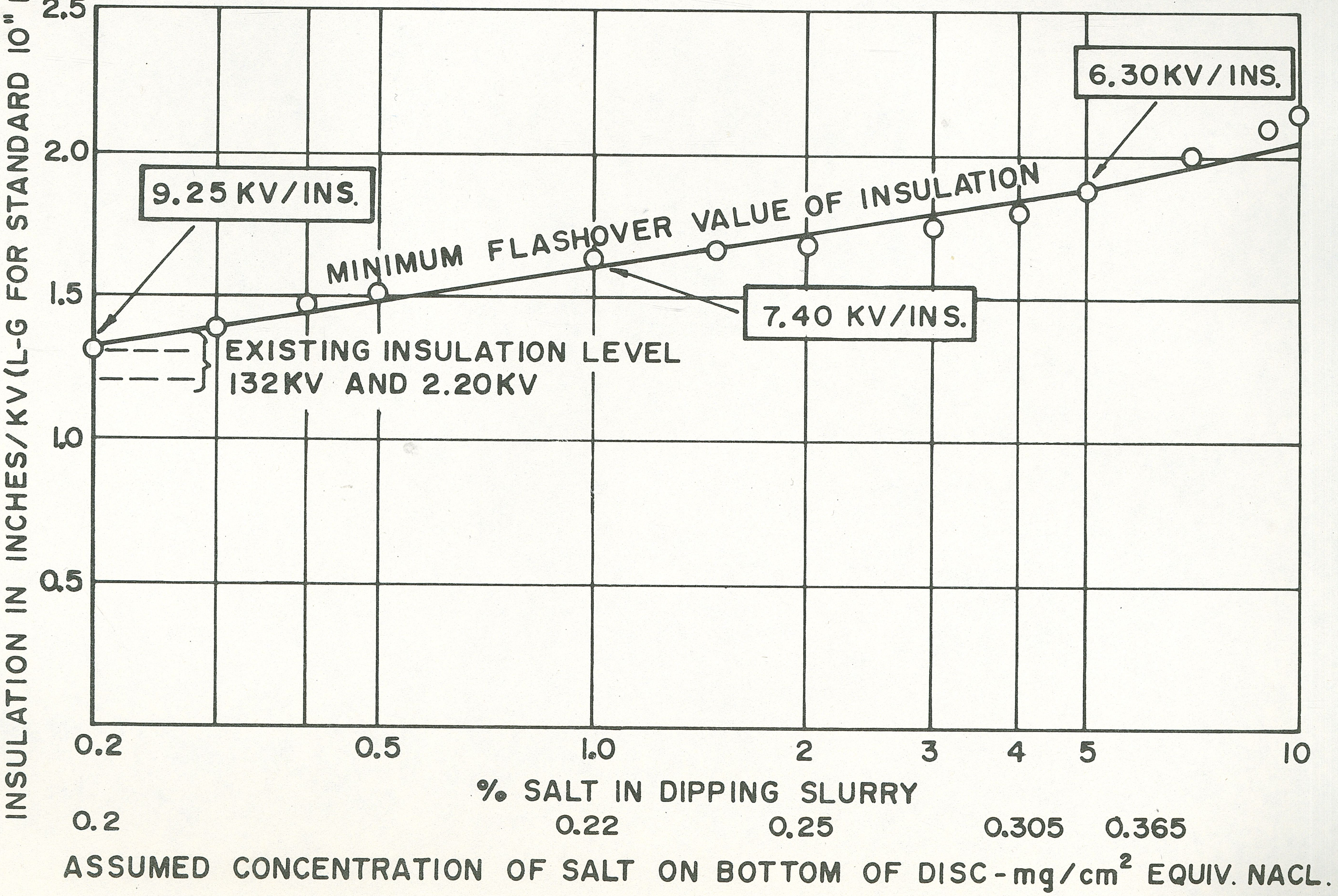

Figure 11. Inches of creepage per kv applied at 60 cycle flashover versus salt content of contaminant. Semi-log plot.

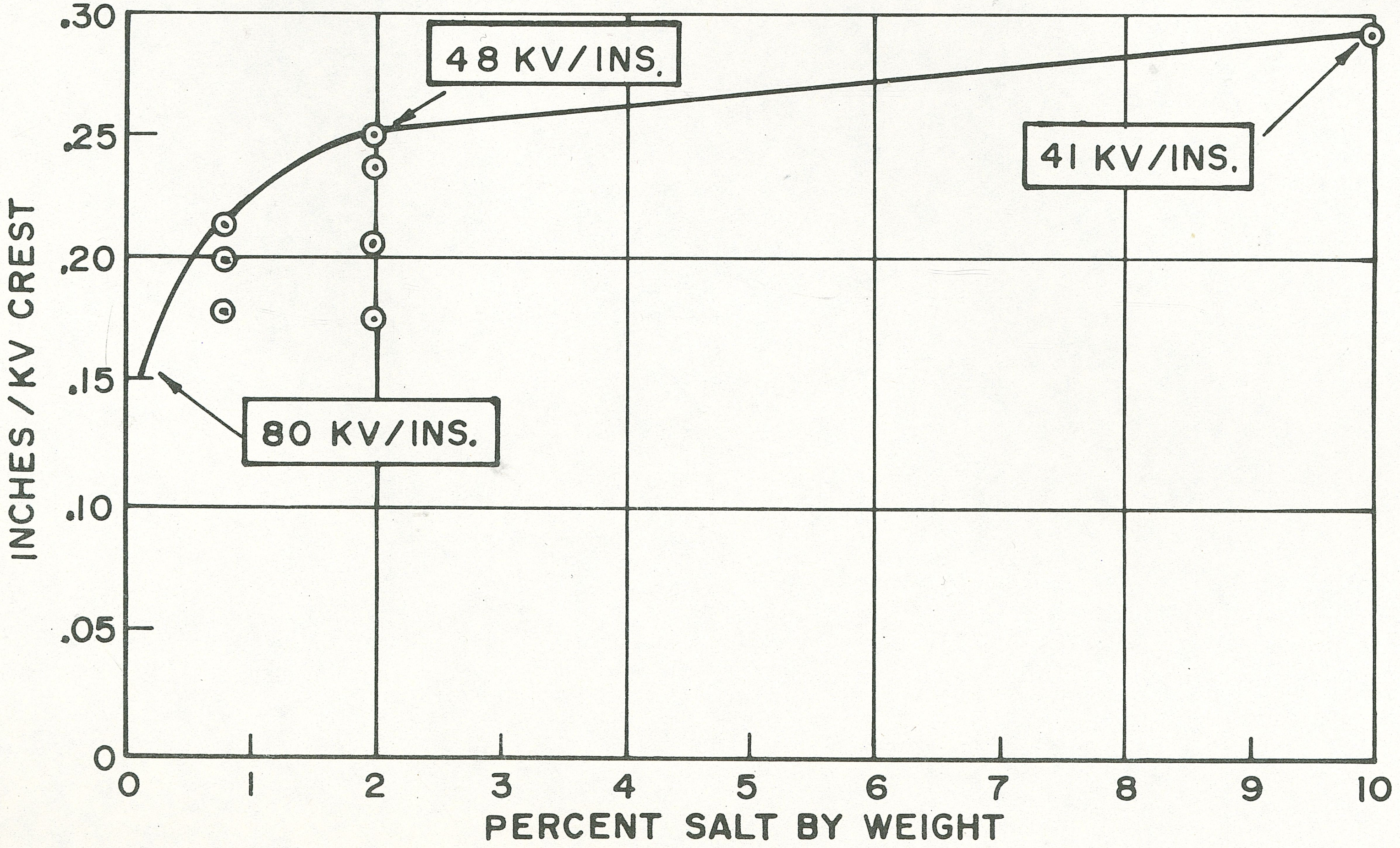

Figure 12. Inches of creepage per kv of switching surge withstand versus salt content of contaminant. All tests made on 15 vertical insulators with positive 140 x 3300 microsecond surges.

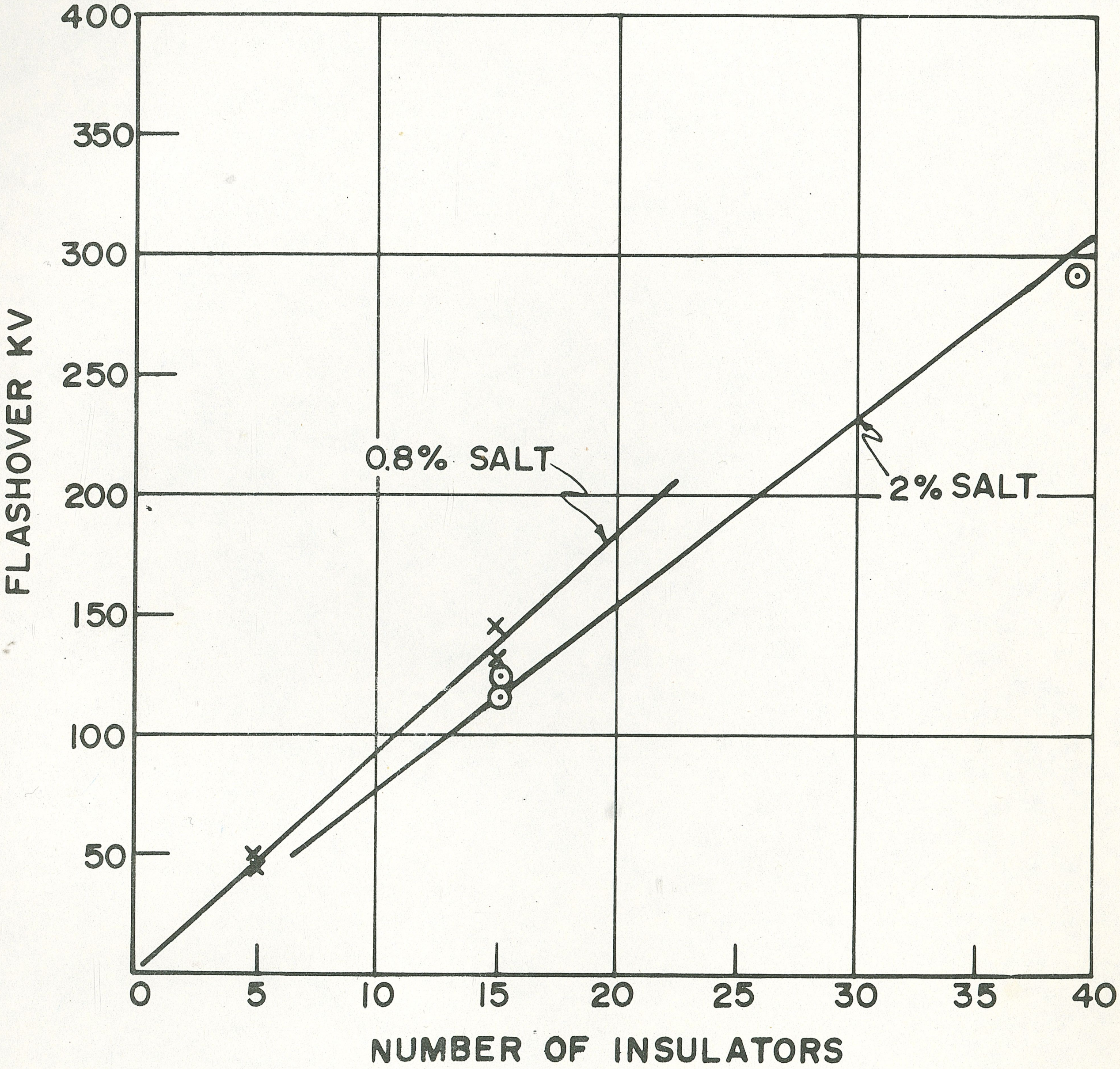

Figure 13. 60 cycle flashover level versus number of insulators for 0.8% and 2.0% salt contaminant.

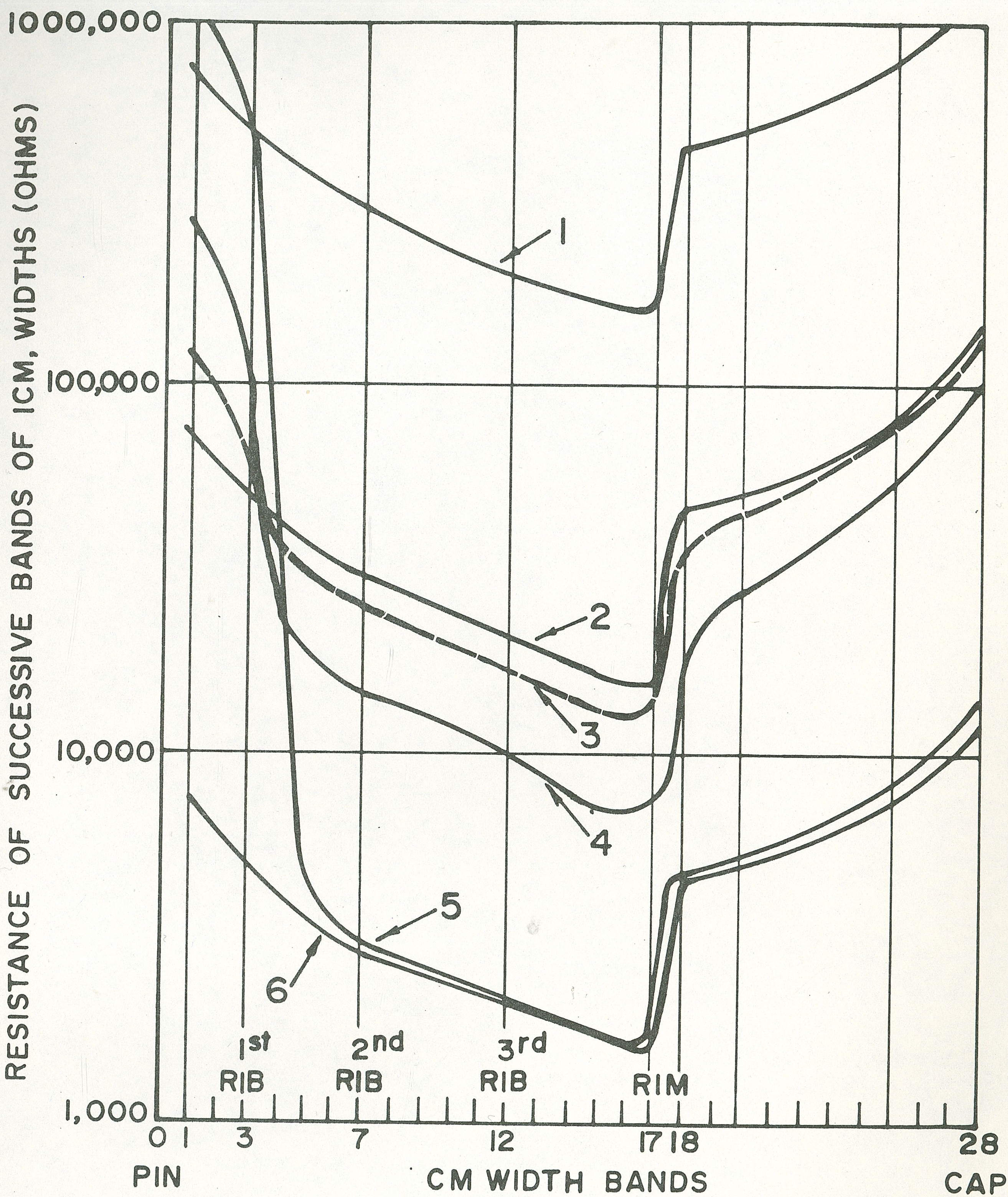

Fig. 14. Resistance of centimeter width bands on a contaminated insulator versus distance in centimeters from the pin (0) to the cap (28)

(1) Approximate dry pollution with no current.
(2) Partially wet resistance 8 minutes after fog start. No current
(3) Distortion by current heating in pin and cap area.
(4) Further distortion by accelerated heating in pin area.
(5) Prior to F/O. Very high resistance at pin. Current very low. Path away from pin tending towards fully wet resistance.
(6) Fully wet resistance, total approximately 130,000 ohms. No current.

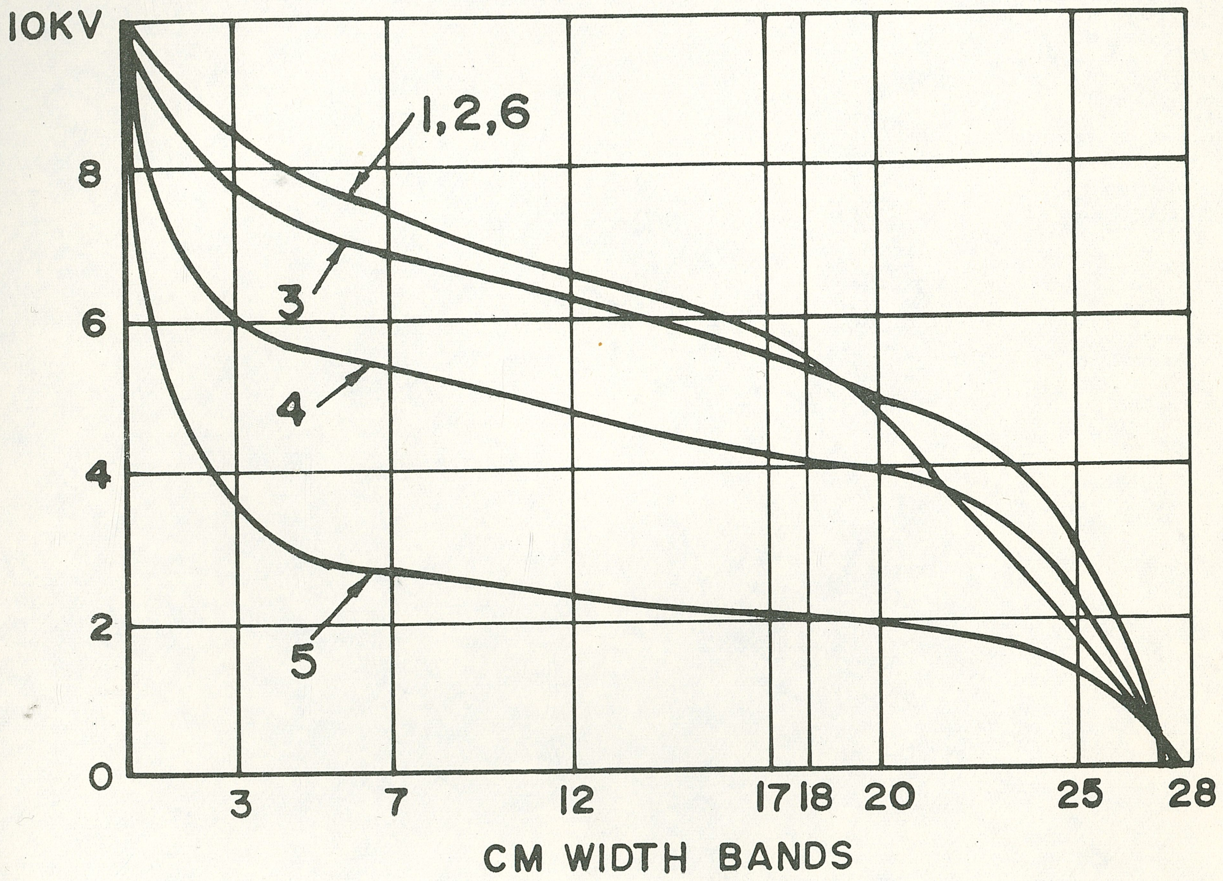

Figure 15. Approximate voltage distribution on contaminated insulators versus distance in centimeters from the pin (0) to the cap (28). Curve designations correspond to resistance curves in Figure 14.

ABSTRACT

The results of field and laboratory tests on contaminated insulators, made to determine insulation level of the S.E.C.V. 500 kv transmission system, are presented, including performance of 220 kv lines operating in a very heavy contamination area, field measurements of the pollution and insulator flashover mechanism, development of artificial pollution for laboratory tests, and the use of this pollution for power frequency and switching surge tests at the General Electric Pittsfield High Voltage Laboratory. Test data includes curves of power frequency and switching surge flashover levels versus contamination severity, power frequency flashover versus string length, and the results of high speed motion picture tests made to determine the basic mechanism of critical surging and flashover on contaminated insulators, plus a theoretical explanation of this mechanism:

KEY WORDS

Insulator contamination, transmission line design, EHV, 500 KV, 60 cycle flashover, switching surge flashover.